Vol 4, №2, 2025 eISSN 2949-1835
PEER-REVIEWED SCIENTIFIC AND PRACTICAL JOURNAL

Modern Trends in Construction, Urban and Territorial Planning

Building Constructions, Buildings and Engineering Structures
Footings and Foundations, Subsurface Structures
Construction Materials and Products
Technology and Organization of Construction
Structural Mechanics
Urban Planning, Rural Settlements Planning
Facilities Life Cycle Management

www.stsg-donstu.ru
DOI 10.23947/2949-1835

Modern Trends in Construction, Urban and Territorial Planning

Peer-reviewed scientific and practical journal (published since 2022)

eISSN 2949–1835
DOI: 10.23947/2949–1835

Vol. 4, no. 2, 2025

A peer-reviewed scientific and practical journal designed to inform the readers about the latest advancements, trends and prospects in the field of construction, architecture, urban planning and adjacent scientific fields. The journal serves a platform for scientific and educational cooperation of researchers and scholars engaged in field of construction.

The journal is included in the List of the leading peer-reviewed scientific publications (Higher Attestation Commission under the Ministry of Science and Higher Education of the Russian Federation), where basic scientific results of dissertations for the degrees of Doctor and Candidate of Science in scientific specialties and their respective branches of science should be published.

The journal publishes articles in the following fields of science:
– Building Constructions, Buildings and Engineering Structures (Engineering Sciences)
– Footings and Foundations, Subsurface Structures (Engineering Sciences)
– Construction Materials and Products (Engineering Sciences)
– Technology and Organization of Construction (Engineering Sciences)
– Structural Mechanics (Engineering Sciences)
– Urban Planning, Rural Settlements Planning (Engineering Sciences)
– Facilities Life Cycle Management (Engineering Sciences)

Indexing and Archiving	RISC, CyberLeninka, CrossRef, Internet Archive
Name of the Body that Registered the Publication	Extract from the Register of Registered Mass Media ЭЛ № ФС 77 – 83923 dated September 16, 2022, issued by the Federal Service for Supervision of Communications, Information Technology and Mass Media
Founder and Publisher	Federal State Budgetary Educational Institution of Higher Education Don State Technical University (DSTU)
Periodicity	4 issues per year
Address of the Founder and Publisher	1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation
E-mail	sovtrendstr@gmail.com
Telephone	+7 (863) 2–738–372
Website	http://www.stsg-donstu.ru/
Date of Publication	30.06.2025

Современные тенденции в строительстве, градостроительстве и планировке территорий

Рецензируемый научно-практический журнал (издается с 2022 года)

eISSN 2949–1835
DOI: 10.23947/2949–1835

Том 4, № 2, 2025

Журнал создан в целях информирования читательской аудитории о новейших достижениях, тенденциях и перспективах в области строительства, архитектуры, градостроительства и смежных научных направлений. Издание является платформой для научно-образовательного сотрудничества российских и иностранных исследователей, вовлеченных в строительную сферу.

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

2.1.1 – Строительные конструкции, здания и сооружения (технические науки)
2.1.2 – Основания и фундаменты, подземные сооружения (технические науки)
2.1.5 – Строительные материалы и изделия (технические науки)
2.1.7 – Технология и организация строительства (технические науки)
2.1.9 – Строительная механика (технические науки)
2.1.13 – Градостроительство, планировка сельских населенных пунктов (технические науки)
2.1.14 – Управление жизненным циклом объектов строительства (технические науки)

Индексация и архивация	РИНЦ, CyberLeninka, CrossRef, Internet Archive
Наименование органа, зарегистрировавшего издание	Свидетельство о регистрации средства массовой информации ЭЛ № ФС 77 – 83923 от 16 сентября 2022 г., выдано Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций
Учредитель и издатель	Федеральное государственное бюджетное образовательное учреждение высшего образования «Донской государственный технический университет» (ДГТУ)
Периодичность	4 выпуска в год
Адрес учредителя и издателя	344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1
E-mail	sovtrendstr@gmail.com
Телефон	+7 (863) 2–738–372
Сайт	http://www.stsg-donstu.ru/
Дата выхода в свет	30.06.2025

CONTENTS

СОДЕРЖАНИЕ

BUILDING CONSTRUCTIONS, BUILDINGS AND ENGINEERING STRUCTURES

СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ, ЗДАНИЯ И СООРУЖЕНИЯ

UDC 69.07
https://doi.org/10.23947/2949–1835-2025-4-2-7-20

Original Empirical Research

EDN: RSCKOZ

Modeling of Shear Strength of Ultra-High-Performance Concrete Beams Using Statistical Learning Tools

Murat M. Tamov[1] ✉, **Olga V. Rudenko**[2], **Mina I.F. Salib**[1]
[1] Kuban State Technological University, Krasnodar, Russian Federation
[2] Kuban State University, Krasnodar, Russian Federation
✉ murat.tamov@gmail.com

Introduction. Ultra-high-performance concrete (UHPC) combines high strength and crack resistance with low permeability, making it ideal for structures operating under aggressive environmental conditions and high loads. The growing use of UHPC in construction makes necessary the development of scientifically grounded methods for designing structures made with this material. The aim of this study is to develop engineering methods for calculating the shear strength of UHPC I-beams using statistical learning techniques. The models were based on extensive datasets, including both the authors' own experimental results and data from other researchers.

Materials and Methods. Artificial neural networks (ANNs) and regression analysis methods were used to develop the models. The tasks were implemented using the STATISTICA software package.

Results. Nonlinear expressions were developed for engineering calculations, allowing for the determination of the shear strength of UHPC-beams accounting for the shear span and structural parameters, including section geometry, UHPC strength characteristics, and fiber and shear reinforcement ratios. The proposed formulas reduce the discrepancy between theoretical and experimental data by up to 2.4 times compared to calculation by methods adopted in codes. The formulas are applicable to beams unreinforced in shear as well as those with fiber and shear reinforcement.

Discussion and Conclusion. The results confirm the applicability of regression models and ANNs for calculating the shear strength of UHPC beams, particularly in cases where traditional analytical solutions are difficult to formalize. The reliability of the developed models is supported by statistical analysis, including verification of regression equation adequacy and comparison with existing code-based methods.

Keywords: ultra-high-performance concrete, I-beams, regression analysis, artificial neural networks, shear force

For citation. Tamov MM, Rudenko OV, Salib MIF. Modeling of Shear Strength of Ultra-High-Performance Concrete Beams Using Statistical Learning Tools, *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):7–20. https://doi.org/10.23947/2949-1835-2025-4-2-7-20

Оригинальное эмпирическое исследование

Моделирование сопротивления поперечным силам балок из сверхвысокопрочного бетона инструментами статистического обучения

М.М. Тамов[1] ✉, **О.В. Руденко**[2], **М.И.Ф. Салиб**[1]
[1]Кубанский государственный технологический университет, г. Краснодар, Российская Федерация
[2] Кубанский государственный университет, г. Краснодар, Российская Федерация
✉ murat.tamov@gmail.com

Аннотация
Введение. Сверхвысокопрочный бетон (СВПБ) сочетает в себе высокую прочность и трещиностойкость, низкую проницаемость, что делает его эффективным для конструкций, эксплуатируемых в условиях действия агрессивных сред и высоких нагрузок. Расширение практики применения СВПБ в строительстве требует разработки соответствующих научно обоснованных методов расчета изготовленных с его применением конструкций. Одним

из малоизученных вопросов является сопротивление изгибаемых СВПБ-конструкций действию поперечных сил. В настоящей работе предложены расчетные зависимости для определения прочности наклонных сечений двутавровых балок из СВПБ, разработанные с применением методов машинного обучения. Для регрессий составлены и структурированы обширные экспериментальные выборки с широкими диапазонами параметров, оказывающих влияние на сопротивление поперечным силам.

Материалы и методы. При построении моделей использованы искусственные нейронные сети (ИНС) и методы регрессионного анализа. Для решения задач использован инструментарий программы STATISTICA.

Результаты исследования. Разработаны нелинейные зависимости для инженерных расчетов, позволяющие производить расчет сопротивления СВПБ-балок поперечным силам с учетом влияния пролета среза нагружения и конструктивных параметров, включая геометрию сечения, прочностные характеристики СВПБ, а также коэффициенты фибрового и поперечного стержневого армирования. Результаты подтверждают применимость регрессионных моделей и ИНС для расчетов прочности наклонных сечений СВПБ-балок, как для сложно формализуемой задачи. Достоверность полученных моделей подтверждена статистическим анализом, включая проверку адекватности уравнений регрессии и их сравнение с нормативными методиками расчета.

Обсуждение и заключение. Предложенные формулы позволяют снизить расхождение между теоретическими и экспериментальными данными в сравнении с нормативными методиками до 2,4 раза. Формулы применимы как для расчета балок с неармированными наклонными сечениями, так и для балок с фибровым и поперечным стержневым армированием.

Ключевые слова: сверхвысокопрочный бетон, двутавровые балки, регрессионный анализ, искусственные нейронные сети, поперечные силы

Для цитирования. Тамов М.М., Руденко О.В., Салиб М.И.Ф. Моделирование сопротивления поперечным силам балок из сверхвысокопрочного бетона инструментами статистического обучения. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):7–20. https://doi.org/10.23947/2949-1835-2025-4-2-7-20

Introduction. Ultra—high-strength concretes (hereinafter referred to as UHPCs) with dispersed (fiber) reinforcement are a relatively new class of concretes characterized by high strength and endurance, durability and frost resistance. Similarly to other types of fine-grained concrete, one of the areas of rational use of UHPC are structures with small cross-sectional profile thicknesses. An example of bent structures of this type are I-beams of superstructures and decking structures operated under the influence of aggressive environments.

The improvement of approaches to calculating the transverse forces of UHPC- beams is largely focused in two directions: construction of finite element models using nonlinear diagrams of deformation of UHPC and reinforcement as well as the refinement of formulas for engineering calculations of beam strength. The formulas of the NF P18-710 manual can be cited as an example of existing regulatory methods for calculating bending SVP structures for transverse forces. Similarly to Eurocode 2, the NF P18-710 formulas are based on the method of truss analogy. At the same time, the Eurocode 2 methodology assumes that all transverse force in elements with transverse reinforcement is perceived only by clamps (concrete resistance is taken into account only in elements without transverse reinforcement). In its turn, in NF P18-710, the resistance (contribution) of concrete is assigned both for elements with and without transverse reinforcement. Separate terms account for the contribution of fiber. What also differs in a way from Eurocode 2 is the NF P18-710 approach to calculating the strength of thin walls. Hence Eurocode 2 provides for this calculation only for elements with transverse reinforcement, while NF P18-710 contains calculation formulas for both elements with and without transverse reinforcement.

The method of calculating transverse forces of SP 360.1325800 "Steel-Reinforced Concrete Structures" replicates that of the set of rules of SP 63.13330 "Concrete and Reinforced Concrete Structures. Basic Provisions" with the replacement of the strength characteristics of ordinary concrete with similar ones of steel-fiber concrete — in the formula for wall strength, R_{fb} is used instead of R_b, and in the formula for calculating inclined sections, R_{fbt} is used instead of R_{bt}. The R_{fbt} resistance corresponds to the top of the deformation diagram of steel fiber concrete under axial tension.

The downside of the normative methods is the incomplete consideration of factors affecting the resistance of beams to transverse forces. This makes it necessary to develop alternative approaches based on the analysis of experimental data and the use of modern computing technologies.

The aim of this study was to obtain engineering methods for calculating the resistance to transverse forces of I-beams by means of statistical learning tools such as neural network and regression analysis. Representative databases were employed as training and test samples of the models, including both the authors' own tests and other researchers' experiments.

Materials and Methods. There are lots of problems facing construction science that cannot be tackled by means of traditional computational methods. In such cases, an accelerated search for new solutions is possible using data management technologies employing a large accumulated volume of results from field and numerical experiments. In materials science literature, this stage of the development of science is referred to as its "fourth paradigm" [1].

In recent years, artificial intelligence technologies have been extensively used for calculating structures as an alternative to classical modeling methods [2] defined as the ability of a computer to simulate intelligent human actions by searching for algorithms for tackling complex problems. A critical part of artificial intelligence is machine learning which is used in order to investigate trends and is aimed at forecasting using algorithms for calculations based on the data involved in training [3]. Machine learning is known for its capacity to capture nonlinear relationships between input and output data that are challenging to formulate. Machine learning has been applied in inspecting and monitoring building structures, optimization, reliability assessment and prediction of material properties [4].

Artificial neural networks (ANN) are computational models that simulate biological neural structures. Their basic elements (neurons) process information by means of dynamically responding to input signals. The key feature of such networks is their adaptability: unlike classical algorithms operating according to strict rules, ANNs are trained on a large amount of data adjusting the parameters of connections. The ANN is based on weighted connections between neurons that constitute an architecture with one or more layers. During the learning process, the system iteratively optimizes the weighting coefficients that determine the strength of the interaction of the elements. For forecasting and regression tasks, single-layer ANNs are commonly used as the simplest type of architecture with direct connections [5, 6].

Analyzing the relationships between processes and factors calls for the use of specialized mathematical methods. *Regression analysis* has become widespread making it possible to quantify the influence of independent variables (predictor factors) on the investigated dependent value (the resulting response).

This method enables one to:

– identify the degree of impact of each factor on the outcome;

– identify the closeness of correlations between the analyzed parameters;

– design predictive models based on the identified dependencies.

In this paper, ANN and regression analysis are used in order to obtain calculation formulas for calculating the resistance to transverse forces of I-beams made of ultra-high-strength concrete and fibrocrete. The STATISTICA toolkit is used to solve the problems.

Research Results. Given the structure of formulas for the strength of inclined sections accepted in the norms, the regression analysis aimed at developing an engineering methodology for calculating I-beam SVP beams was carried out in two stages. At the first stage, a regression model of the strength of beams with no fiber and rod transverse reinforcement was obtained

$$Q = Q_b = f(x_1, x_2, x_3, x_4, x_5, x_6), \quad (1)$$

where x_1 (a/h_0), x_2 (b_w), x_3 (h_0), x_4 (R), x_5 (μ_s), x_6 (φ_f) are factor arguments; a/h_0 is a section span; b_w and h_0 is the wall thickness and working section height; R is the strength of concrete; μ_s is the coefficient of longitudinal reinforcement.

$$\varphi_f = \frac{(b_f - b_w) \cdot t_f}{b_w \cdot h_0},$$

where b_f, t_f is the width and thickness of the shelf.

The database for the first stage was a sample based on the results of transverse force tests of rectangular and I-beams made of high-strength and ultra-high-strength concrete with no fiber and transverse core reinforcement discussed in literature [7–41].

At the second stage, the load-bearing capacity of beams reinforced with fibers and having no rod transverse reinforcement is assumed to be equal to:

$$Q = Q_b + Q_f,$$

after that, the formula for the contribution of fibers Q_f was identified by selecting the parameters of a regression model in the following form

$$Q = y + f(x_1, x_2, x_3, x_4),$$

where y is the contribution of concrete Q_b according to formula (1); x_1 (b_w), x_2 (h_0), x_3 (R_{bt}), x_4 (μ_s).

The database for the second stage was compiled based on the results of our and other tests for the transverse force of T- and I- UHPC beams reinforced with fibers but with no transverse reinforcement. [7, 13, 36, 37, 39, 42–49].

At both stages, the order is set for obtaining regression dependencies:

1. Choosing a functional form.

2. Assessing the model parameters.

3. Testing the validity of the model.

Choosing a functional form for Q_b is carried out by visual analysis instrumental in the initial assessment of data, identifying common patterns and trends. As it is possible to design only three-dimensional graphs (surfaces), a few of them will be required for visual analysis of the dependence. Having considered these surfaces (Fig. 1), the equation of dependence of the variable y on x_1, x_2, x_3 and x_4 should have a complex nonlinear form.

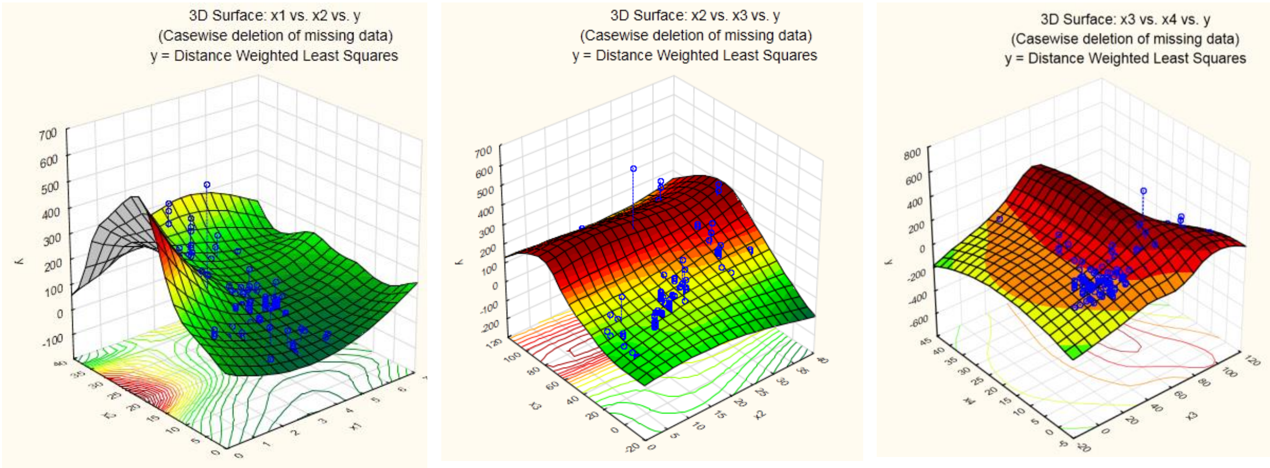


Fig. 1. Three-dimensional graphs (surfaces) of the dependence y on x_1, x_2, x_3 and x_4

In order to visualize descriptive statistics of experimental data, so-called "box diagrams" are designed (Fig. 2) that can be used for the data to be evaluated for distribution structure, outliers, uniformity of observations, etc. As can be seen, the variables x_1, x_5 and x_6 are closely located near their average value. The variables x_2, x_3, x_4 and y have a symmetrical distribution. The dependent variable y has the largest variation.

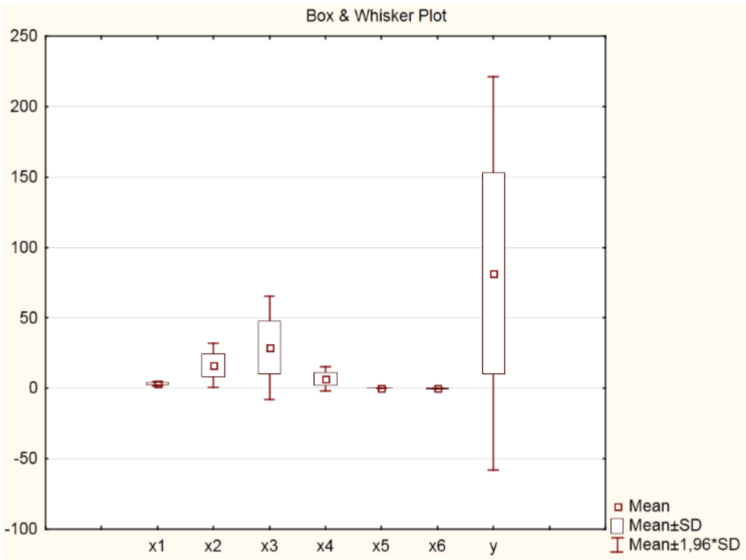


Fig. 2. «Box» diagrams

In order to rule out multicollinearity of variables, a matrix of paired correlation coefficients has been compiled (Fig. 3). It is believed that the presence of correlation coefficients over 0.75–0.80 in absolute value indicates multicollinearity between variables. In order to eliminate multicollinearity, these factors must be excluded from the model.

Color map of correlations (Spreadsheet1)
N=217 (Casewise deletion of missing data)
r>= -1, -0,80, -0,60, -0,40, -0,20, 0, 0,20, 0,40, 0,60, 0,80, 1

Variable	x1	x2	x3	x4	x5	x6	y
x1	1,000000	0,115219	-0,010061	-0,062375	-0,007534	-0,015013	-0,185571
x2	0,115219	1,000000	0,595526	-0,099337	-0,088854	-0,304818	0,655836
x3	-0,010061	0,595526	1,000000	-0,015954	-0,089723	-0,014764	0,716017
x4	-0,062375	-0,099337	-0,015954	1,000000	0,235650	0,420090	0,141043
x5	-0,007534	-0,088854	-0,089723	0,235650	1,000000	0,158945	0,212631
x6	-0,015013	-0,304818	-0,014764	0,420090	0,158945	1,000000	-0,069764
y	-0,185571	0,655836	0,716017	0,141043	0,212631	-0,069764	1,000000

Fig. 3. Diagram of correlations

In our case, there might be multicollinearity between variables x_2 and x_3. For verification, a method was used to analyze the sensitivity of input variables while building a neural network model — the process of evaluating the influence of input variables (features) on the output of the model, i.e., on the result of forecasting or classification. This analysis enables us to assess how changes in the input data or model parameters affect the output of the neural network and helps us understand which features are most important for the model and which of them can be excluded (Fig. 4).

	Sensitivity analysis (Spreadsheet1) Samples: Train					
Networks	x3	x2	x5	x1	x4	x6
5.MLP 6-3-1	4,656816	3,938443	3,029732	1,856225	1,091346	1,005235

Fig. 4. Sensitivity analysis of *y*

While building a neural network model, all the input variables received sensitivity values greater than 1. This means that all of the 6 input variables should be retained in our regression equation.

Identifying the coefficients of the model Q_b was carried out using the least square method (LSM) that involves a range of statistical prerequisites being met. The most important of these conditions is homoscedasticity, the constancy of the variance of random errors in the model. Violation of this requirement (heteroskedasticity) results in the following: the application of Student's t-test and Fischer's F-test becomes incorrect. Hence in the presence of heteroscedasticity, the results of regression analysis cannot be considered statistically reliable.

The STATISTICA package makes use of graphical analysis in order to identify heteroscedasticity. To this end, a graph is deisgned where the values of the variable y are plotted along the abscissa axis, and its deviations along the ordinate axis (Fig. 5). As can be seen, the values are randomly distributed (exceeding confidence limits) causing one to assume that there is no heteroscedasticity.

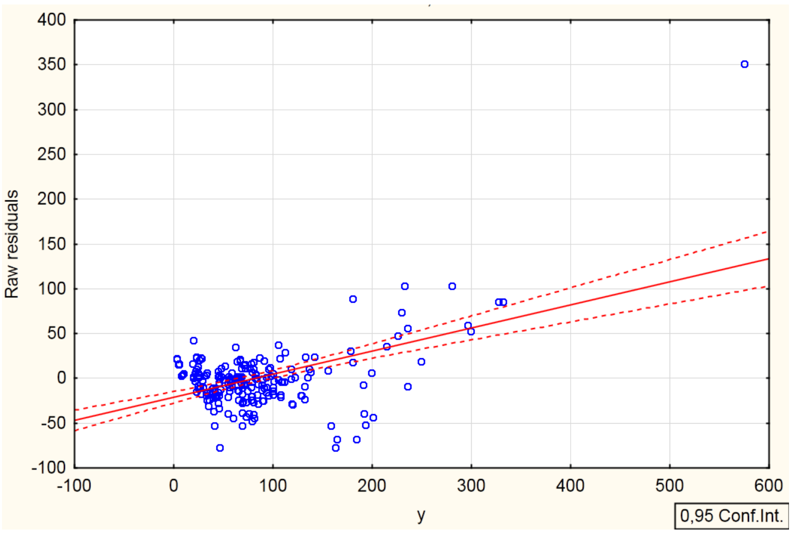


Fig. 5. Graph of the dependence of the residuals on the variable *y*

Hence the calculation of the parameters of the nonlinear regression equation can be calculated using LSM. To this end, the user regression block of the STATISTICA program is used allowing one to enter an arbitrary type of equation. It is based on a complex nonlinear model taking the following form:

$$y = a_0 {x_1}^{m1} x_2 x_3 {x_4}^{m2} {x_5}^{m3} (1 + a_1 x_6)\left(1 + a_2 \frac{1}{\sqrt{x_3}}\right). \quad (2)$$

The results of assessing the parameters a_0, a_1, a_2, m_1, m_2 and m_3 of function (2) in the STATISTICA software are presented in Fig. 6. The first column of the table contains estimates of the regression parameters making it possible to write an analytical representation of the equation:

$$y = 1{,}466 {x_1}^{-1{,}14} x_2 x_3 {x_4}^{0{,}2} {x_5}^{0{,}6} (1 + 1{,}6 x_6)\left(1 + 9{,}4 \frac{1}{\sqrt{x_3}}\right). \quad (3)$$

Column 3 contains calculated values of t-statistics, quantifying the significance of the predictor effect on the dependent variable. This indicator is calculated as the following ratio:

t = (coefficient estimates)/(standard error of the coefficient).

The value of the indicator reflects the number of standard deviations by which the coefficient estimate differs from zero. It has been empirically found that coefficients with t-values beyond [–2;2] have sufficient reliability to be used in predictive models. At the same time, the higher the absolute value of statistics, the less likely it is that the coefficient will be mistakenly recognized as significant and the forecasts of the model will be more stable.

The fourth column contains the p-values that are the lowest levels of significance (probability of rejection of a fair hypothesis) for which the calculated verification statistics lead to rejection of the null hypothesis. To this end, the p-value is compared with the generally accepted standard significance levels of 0.05 or 0.01.

Model is: v7=a0*v1^m1*v2*v3*v4^m2*v5^m3*(1+a1*v6)*(1+a2*v3^(-0.5)) (Spreadsheet105)
Dep. Var. : Q_b
Level of confidence: 95.0% (alpha=0.050)

	Estimate	Standard error	t-value df = 211	p-value	Lo. Conf Limit	Up. Conf Limit
a0	1.46615	0.348623	4.2055	0.000038	0.77892	2.15338
m1	-1.13779	0.059233	-19.2086	0.000000	-1.25455	-1.02102
m2	0.19068	0.032669	5.8366	0.000000	0.12628	0.25508
m3	0.59965	0.030337	19.7659	0.000000	0.53984	0.65945
a1	1.60835	0.350377	4.5903	0.000008	0.91766	2.29904
a2	9.37469	2.217515	4.2276	0.000035	5.00337	13.74602

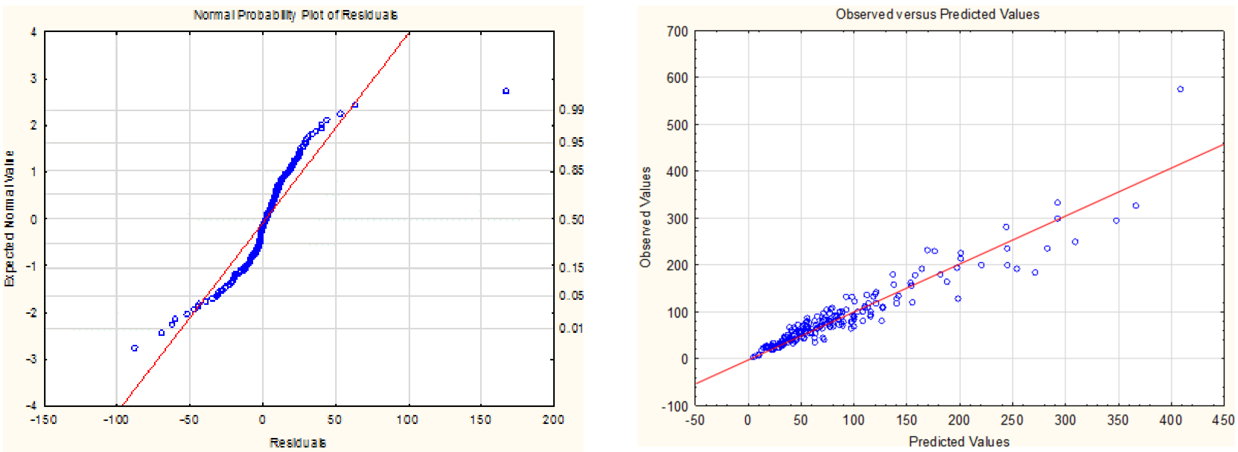
Results: Spreadsheet105

```
Model is: v7=a0*v1^m1*v2*v3*v4^m2*v5^m3*(1+a1*v6)*(1+a2*v3^(-0.5))
Dependent variable: Qb                    Independent variables: 6
Loss function: least squares
Final value: 107391.0904578
Proportion of variance accounted for: .90184442     R =.9496549
```

Fig. 6. Result of calculating the parameters of the regression equation Q_b

Based on the values of the above parameters shown in Fig. 6 and the high values of the multiple correlation index (R ≈ 0.95), it can be argued the parameters of equation (3) are statistically significant.

The validity of the model is closely associated with the fulfillment of the basic assumptions regarding the regression residuals ε_i which include the independence and absence of autocorrelation of the residuals, as well as their normal distribution. If the chosen regression model describes the true dependence well, the residuals should be independent normally distributed random variables with zero mean. In the residue distribution diagram (Fig. 7*a*), the points lie along a straight line — the residue distribution is normal. In the scattering diagram (Fig. 7*b*) the points are located close to a straight line drawn at an angle of 45 ° to the coordinate axes. This indicates that the response is close to the observed values.



a) *b)*

Fig. 7. Distribution diagrams: *a* — of the residuals; *b* — of scattering

At the *second stage* of the regression analysis, a dependence was designed for the strength of UHPC beams with fiber reinforcement with no bar cross reinforcement. A general view of the function is the following:

$$Q = Q_b + Q_f.$$

Inserting y instead of Q_b calculated based on (3) and replacing the contribution of the fibers with the function from x_1 (b_w), x_2 (h_0), x_3 (R_{bt}), x_4 (μ_s), we get

$$Q = y + f(x_1, x_2, x_3, x_4). \quad (4)$$

In order to calculate the basic statics of all of the factors of the model, a matrix of paired correlations was designed (Fig. 8). It was found that the arguments x_2 and y have a very high pair correlation (more than 0.7).

Variable	Correlations (Spreadsheet1) Marked correlations are significant at p < ,05000 N=56 (Casewise deletion of missing data)							
	Means	Std.Dev.	x1	x2	x3	x4	y	Q
x1	4,4821	0,9861	1,000000	0,031394	0,216939	-0,508297	0,166597	0,276947
x2	37,6357	18,9912	0,031394	1,000000	0,616026	-0,203521	0,831776	0,783928
x3	1,3526	0,5999	0,216939	0,616026	1,000000	-0,573725	0,597728	0,635939
x4	0,0394	0,0187	-0,508297	-0,203521	-0,573725	1,000000	-0,253158	-0,160484
y	98,9823	53,7237	0,166597	0,831776	0,597728	-0,253158	1,000000	0,834242
Q	279,6782	183,3429	0,276947	0,783928	0,635939	-0,160484	0,834242	1,000000

Fig. 8. Matrix of paired correlations

The analysis of paired correlation coefficients enabled us to identify only explicit cases of linear relationship between the predictors. However, the key problems in designing multiple regression models lie in multicollinearity, a situation where there is a systemic linear relationship between several factors at a time. In order to quantify the degree of multicollinearity, an analysis of the determinant of the correlation matrix of factors is used. The closer the determinant value is to zero, the higher the degree of linear dependence between the variables and the more distinct the problem of multicollinearity, as well as the less reliable estimates of the model parameters (Fig. 9).

$$R := \begin{pmatrix} 1 & 0.031394 & 0.216939 & -0.508297 & 0.166597 & 0.276947 \\ 0.031394 & 1 & 0.616026 & -0.203521 & 0.831776 & 0.783928 \\ 0.216939 & 0.616026 & 1 & -0.573725 & 0.597728 & 0.635939 \\ -0.508297 & -0.203521 & -0.573725 & 1 & -0.253158 & -0.160484 \\ 0.166597 & 0.831776 & 0.597728 & -0.253158 & 1 & 0.834242 \\ 0.276947 & 0.783928 & 0.635939 & -0.160484 & 0.834242 & 1 \end{pmatrix}$$

$$detR := |R| \qquad detR = 0.014$$

Fig. 9. Calculation of the determinant of the matrix of paired correlation coefficients

Proximity to zero of the determinant of the matrix of paired correlation coefficients (*detR* = 0,014) means that there is multicollinearity between the arguments. One of the ways to account for the internal correlation of factors is to switch to combined regression equations, i.e. to those reflecting not only the influence of the factors, but also their interaction. A combination of our factor arguments in the model $Q = y + f(x_1, x_2, x_3, x_4, x_1 \cdot x_2 \cdot x_3 \cdot x_4)$ will thus be included in the first degree and specification will be a complex linear dependence. The nonlinear nature of the relationship of the model is confirmed by means of the shapes of the constructed three-dimensional surfaces of the dependence of the variable Q on its arguments (Fig. 10).

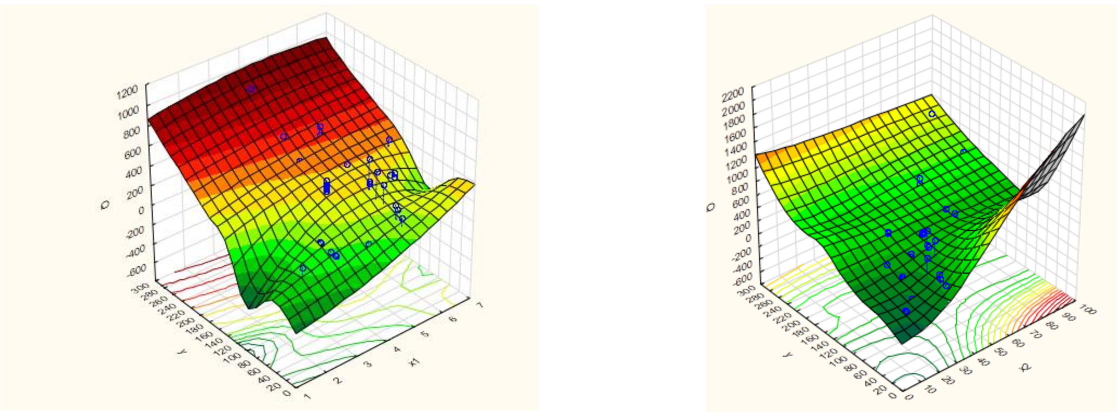


Fig. 10. Three-dimensional graphs (surfaces) of the dependence of Q on x_1 and x_2

The sensitivity analysis (Fig. 11) indicates the need to participate in the regression of all of the variables, with the largest contribution expected to be made by the variable y (contribution of concrete Q_b).

Networks	Sensitivity analysis (Spreadsheet1) Samples: Train				
	y	x2	x4	x3	x1
1.MLP 5-4-1	106,7567	30,73866	8,477698	8,374472	2,453012

Fig. 11. Sensitivity analysis of *Q*

As a result of the study, it was decided to use the dependency as a model specification:

$$Q = y + a_0 x_1 x_2 x_3{}^{m3} x_4{}^{m4}\left(1 + 2\frac{1}{\sqrt{x_2}}\right). \qquad (5)$$

The results of *assessing the parameters* of regression in the software STATISTICA are shown in Fig. 12.

Having substituted the parameter values in (5), the following general form of the equation is obtained:

$$Q = y + 5{,}46 x_1 x_2 x_3{}^{0{,}95} x_4{}^{0{,}65}\left(1 + 2\frac{1}{\sqrt{x_2}}\right).$$

The values of the *t*-value and the *p*-value indicate a good selection of the regression equation and the statistical significance of its coefficients (Fig. 13). The multiple correlation index *R* = 0.91 highly evaluates the proximity of the combined influence of the factors on the result.

	Model is: v6=v5+a0*v1*v2*v3^m1*v4^m2*(1+2*v2^(-0.5)) (Spreadsheet108) Dep. Var. : **Q** Level of confidence: 95.0% (alpha=0.050)					
	Estimate	Standard error	t-value df = 53	p-value	Lo. Conf Limit	Up. Conf Limit
a0	5.458100	2.014278	2.709706	0.009052	1.417971	9.498230
m1	0.948995	0.205740	4.612603	0.000026	0.536334	1.361656
m2	0.646525	0.127836	5.057442	0.000005	0.390117	0.902932

Results: Spreadsheet108 ?

```
Model is: v6=v5+a0*v1*v2*v3^m1*v4^m2*(1+2*v2^(-0.5))
Dependent variable: Q                    Independent variables: 5
Loss function: least squares
Final value: 322009.0360973
Proportion of variance accounted for: .82582846     R =.90875105
```

Fig. 12. Result of calculating the parameters of the regression equation *Q*

Effect	Model is: v6=v5+a0*v1*v2*v3^m3*v4^m4*(1+2*v2^(-0,5)) (Spreadsheet1) Dep. Var. : Q				
	1 **Sum of Squares**	2 DF	3 Mean Squares	4 F-value	5 p-value
Regression	5907108	3,00000	1969036	324,0869	0,00
Residual	322009	53,00000	6076		
Total	6229117	56,00000			
Corrected Total	1848804	55,00000			
Regression vs.Corrected Total	5907108	3,00000	1969036	58,5768	0,00

Fig. 13. Results of the multidimensional dispersion analysis

The fourth column (Fig. 13) shows Fischer's F-statistics which serve to *check the validity of the model*. The fifth column (p) shows the significance of Fischer's F-statistics – the critical value of the quantile of the Fischer distribution rejecting the null hypothesis of the absence of the factor influence. The statistical significance of the regression equation is thus recognized, i.e. there is a relationship between the above features, and the observational results are in good agreement with the assumption of its specification. The normal probability graph (Fig. 14) confirms the normal distribution of the residuals of the regression model.

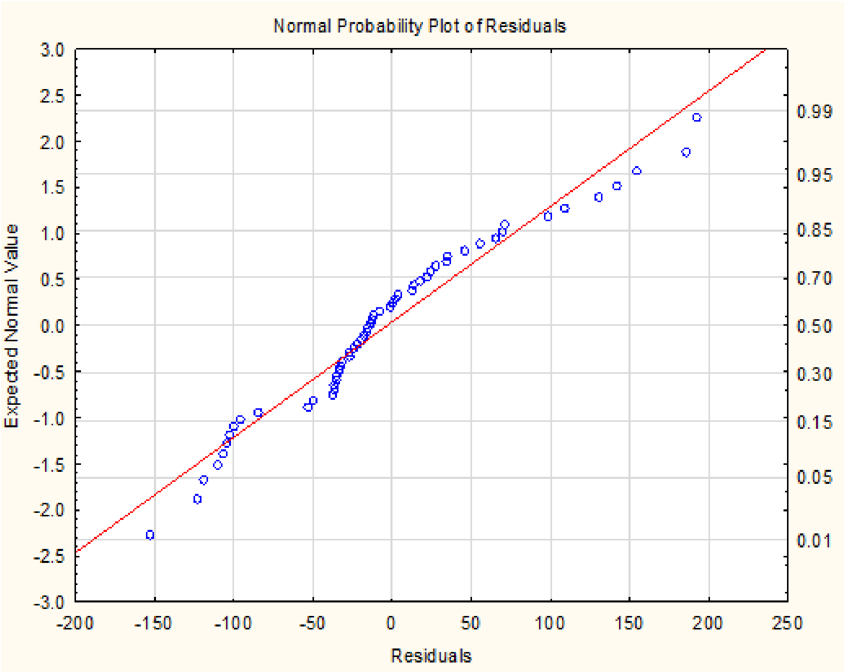


Fig. 14. Diagrams of the distribution of the residuals

The autocorrelation between the arguments of the model leads one to struggle confirming the correctness of the choice of specification. In this case, it is necessary to perform a comparative analysis between alternative regression models. E.g., as an alternative, quation (6) of the joint influence can be taken without accounting for the factor x_2:

$$Q = a_0 x_1^{m_1} x_3^{m_3} x_4^{m_4} y \qquad (6)$$

The resulting parameters of this regression are in Fig. 15.

Model is: v6=a0*v1^m1*v3^m3*v4^m4*v5 (Spreadsheet1)
Dep. Var. : Q
Level of confidence: 95.0% (alpha=0.050)

	Estimate	Standard error	t-value df = 52	p-value	Lo. Conf Limit	Up. Conf Limit
a0	3,640638	1,354431	2,687946	0,009635	0,922773	6,358504
m1	0,471554	0,205487	2,294819	0,025811	0,059215	0,883893
m3	0,428909	0,123765	3,465514	0,001069	0,180556	0,677261
m4	0,323869	0,089391	3,623062	0,000661	0,144493	0,503245

Fig. 15. Result of calculating the parameters of the regression equation (6)

The classic determination coefficient R^2 ranging from 0 to 1 serves as a basic indicator of the explanatory ability of the model. Nevertheless this indicator has a considerable limitation: its value increases monotonously as any of the regressors is added, even statistically insignificant ones. This effect is due to the mathematical nature of R_2 itself making it unsuitable for comparing models with different numbers of predictors and choosing the optimal specification. In order to overcome these disadvantages, alternative approaches have been developed, such as the use of adjusted R_2 allowing for a more objective comparison of models of different dimensions, but also protects the limitations of the original R_2 method, and the Akaike information criteria (AIC) and the Bayesian Schwarz criterion (BIC/SC). The AIC criterion is less strict on the number of parameters and is preferable for small samples, while BIC/SC penalizes the complexity of the model more severely, estimates large data more precisely, and accounts for the sample size in the penalty formula. Hence the specification with the minimum value of the information criterion (AIC or BIC) will be considered optimal, reflecting a compromise between the accuracy of the data description and the complexity of the model.

In Table 1, the information indicators of the selected model specification (5) are compared with (6) calculation formulas SP 360.1325800, as well as with formulas FIB Model code 2010 and RILEM TC 162-TDF. As can be seen, all 4 metrics have the lowest value for the selected specification (5).

Table 1

Quality indicators of the regression equation

Equation	MSE	MAPE	AIC	BIC
(5)	6110.08	26.78 %	500.19	657.57
(6)	7506.72	28 %	511.72	669.11
СП 360.1325800	30528.81	47 %	590.28	757.35
FIB Model code 2010	56070.45	57 %	624.32	811.49
RILEM TC 162-TDF	24092.38	42 %	577.02	750.69

The accuracy of the proposed methods for calculating the strength of I-UHPC beams under the action of transverse forces was assessed by comparing the theoretical and experimental values of destructive loads based on a sample of data obtained from the relevant published experimental studies [7, 13, 32, 36, 37, 42–50]. The values of destructive loads are identified as follows:

$$Q_{\text{per}} = Q_{b,\text{per}} + Q_{f,\text{per}} + Q_{sw},$$

where $Q_{b,\text{per}}$ and $Q_{f,\text{per}}$ are the contributions of concrete and fibers based on (3) and (4).

Tables 2–4 provide a comparative assessment of the accuracy of the suggested regression and standard calculation methods. At the same time, beams with no fiber reinforcement are calculated according to the formulas of SP 63.13330, ACI 318M and Eurocode 2, and beams with fiber reinforcement are calculated according to the formulas of SP 360.1325800, designed for steel-fiber structures, and according to the formulas FIB Model code 2010 and RILEM TC 162-TDF for UHPC structures.

Table 2

Comparison of the experimental Q_{exp} and theoretical Q_{calc} values of the strength of UHPC-beams *with no fiber and transverse rod reinforcement*

Indicator	Calculation method			
	Regression	SP 63.13330	ACI 318M	EC 2
Mean deviation in % $\left(\frac{Q_{exp} - Q_{calc}}{Q_{exp}}\right) \cdot 100$	17	40	29	21
Mean value of the ratio Q_{exp}/Q_{calc}	1.03	1.45	1.34	1.2
Coefficient of the ratio variation Q_{exp}/Q_{calc}	0.22	0.43	0.44	0.56

Table 3

Comparison of the experimental Q_{exp} and theoretical Q_{calc} values of the strength of UHPC beams with fibers and with no *transverse rod reinforcement*

Indicator	Calculation method			
	Regression	SP 360.1325800	FIB Model code 2010	RILEM TC 162-TDF
Mean deviation in % $\left(\frac{Q_{exp} - Q_{calc}}{Q_{exp}}\right) \cdot 100$	26	47	57	42
Mean value of the ratio Q_{exp}/Q_{calc}	1	2.46	2.76	1.85
Coefficient of the ratio variation Q_{exp}/Q_{calc}	0.29	0.64	0.42	0.41

Table 4

Comparison of the experimental Q_{exp} and theoretical Q_{calc} values of the strength of UHPC beams with fibers and with no *transverse rod reinforcement*

Indicator	Calculation method			
	Regression	SP 360.1325800	FIB Model code 2010	RILEM TC 162-TDF
Mean deviation in % $\left(\frac{Q_{exp} - Q_{calc}}{Q_{exp}}\right) \cdot 100$	28	37	39	39
Mean value of the ratio Q_{exp}/Q_{calc}	1.19	1.71	1.76	1.81
Coefficient of the ratio variation Q_{exp}/Q_{calc}	0.33	0.44	0.43	0.38

The highest accuracy of the regression model is achieved in the absence of fiber and transverse core reinforcement of beams: the average difference between the experimental and theoretical values in this case is 17%. While calculating beams with fibers and clamps, the error is expected to increase, reaching 28%. As can be seen, the average value of the ratio Q_{exp}/Q_{calc} was 1.19, i.e. the deviation is formed towards the margin.

Discussion and Conclusion. The results presented by the obtained regression models indicate the possibility of calculating the contribution of concrete and fibers to the resistance of the UHPC beams to transverse forces. The assessment of the quality and reliability of the models is confirmed by using a set of metrics and comparing them with alternatives. The calculation based on the developed regressions improves the convergence of theoretical and experimental results by up to 2.4 times compared to the formulas of norms. The synthesis of statistical methods and artificial intelligence tools opens up avenues for further improvement of methods for calculating building structures, particularly in cases of tasks which are difficult to formalize where designing traditional analytical solutions is challenging.

References

1. Agrawal A, Choudhary A Perspective: Materials Informatics and Big Data: Realization of the "Fourth Paradigm" of Science in Materials Science. *APL Materials*. 2016;4:1–10. https://doi.org/10.1063/1.4946894

2. Jasmine PH, Arun S Machine Learning Applications in Structural Engineering - a Review. *IOP Conference Series: Materials Science and Engineering*. 2021;1114. https://doi.org/10.1088/1757-899X/1114/1/012012

3. Salehi H Emerging Artificial Intelligence Methods in Structural Engineering. *Engineering Structures*. 2018;171:170–189. https://doi.org/10.1016/j.engstruct.2018.05.084

4. Falcone R, Lima C, Martinelli E Soft Computing Techniques in Structural and Earthquake Engineering: a Literature Review. *Engineering Structures*. 2020;207(4):1–16. https://doi.org/10.1016/j.engstruct.2020.110269

5. Keshtegar B, Bagheri M, Yaseen ZM Shear Strength of Steel Fiber-Unconfined Reinforced Concrete Beam Simulation: Application of Novel Intelligent Model. *Composite Structures*. 2019;212:230–242. https://doi.org/10.1016/j.compstruct.2019.01.004

6. Hosseini Gh Capacity Prediction of RC Beams Strengthened with FRP by Artificial Neural Networks Based on Genetic Algorithm. *Journal of Soft Computing in Civil Engineering*. 2017;1(1):93–98. https://doi.org/10.22115/scce.2017.48392

7. Salib MIF, Tamov MM Strength of Inclined Sections (Shear Strength) of I-shaped Beams Made of Ultra-High-Performance Concrete. *Engineering Journal of Don*. 2024;109(1):369–381. http://www.ivdon.ru/ru/magazine/archive/n1y2024/8952 (accessed: 04.05.2025)

8. Adebar P, Collins MP Shear Strength of Members Without Transverse Reinforcement. *Canadian Journal of Civil Engineering*. 1996;23(1):30–41. https://doi.org/10.1139/l96-004

9. Ahmad SH, Khaloo AR Shear Capacity of Reinforced High-Strength Concrete Beams. *ACI Journal, Proceedings*. 1986;83(2):297–305.

10. Ahmad SH, Xie Y, Yu T Shear Strength of Reinforced Lightweight Concrete Beams of Normal and High Strength Concrete. *Magazine of Concrete Research*. 1994;46(166):57–66. https://doi.org/10.1680/macr.1994.46.166.57

11. Ahmad SH, Park F, El-Dash K Web Reinforcement Effects on Shear Capacity of Reinforced High-Strength Concrete Beams. *Magazine of Concrete Research*. 1995;47(172):227–233. https://doi.org/10.1680/macr.1995.47.172.227

12. Arowojolu O, Ibrahim A, Almakrab A, Saras N, Nielsen R Influence of Shear Span-to-Effective Depth Ratio on Behavior of High-Strength Reinforced Concrete Beams. *International Journal of Concrete Structures and Materials*. 2021;15(1):1–12. https://doi.org/10.1186/s40069-020-00444-7

13. Baby F, Marchand P, Toutlemonde F Shear Behavior of Ultrahigh Performance Fiber-Reinforced Concrete Beams. I: Experimental Investigation. *Journal of Structural Engineering*. 2014;140(5):1–10. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000907

14. Bae B-I, Lee M-S, Choi C-S, Jung H-S, Choi H-K Evaluation of the Ultimate Strength of the Ultra-High-Performance Fiber-Reinforced Concrete Beams. *Applied Sciences*. 2021;11(7):1–17. https://doi.org/10.3390/app11072951

15. Bazant ZP, Kazemi MT Size Effect on Diagonal Shear Failure of Beams without Stirrups. *ACI Journal*. 1991;88(3):268–276. URL: http://www.civil.northwestern.edu/people/bazant/PDFs/Papers/273.pdf (accessed: 04.05.2025).

16. Bohigas AC *Shear Design of Reinforced High-Strength Concrete Beams*. University of the Balearic Islands; 2002. URL: https://www.researchgate.net/publication/263696608_Shear_design_of_reinforced_high-strength_concrete_beams (accessed: 04.05.2025).

17. Bui T, Nana WSA, Doucet-Ferru B, Bennani A, Lequay H, Limam A Shear Performance of Steel Fiber Reinforced Concrete Beams Without Stirrups: Experimental Investigation. *International Journal of Civil Engineering*. 2020;18(5):865–881. https://doi.org/10.1007/s40999-020-00505-8

18. Collins MP, Kuchma D How safe are our large, lightly reinforced concrete beams, slabs and footings? *ACI Structural Journal*. 1999;96(4):482–490.

19. Elzanaty AH, Nilson AH, Slate FO Shear Capacity of Reinforced Concrete Beams Using High-Strength Concrete. *ACI Journal*. 1986;83(2):290–296.

20. González-Fonteboa B *Hormigones con áridos reciclados procedentes de demoliciones: dosificaciones, propiedades mecánicas y comportamiento estructural a cortante*. Universidad de la Coruña; 2002. (in Spanish)

21. Hamrat M, Boulekbache B, Chemrouk M, Amziane S Shear Behaviour of RC Beams without Stirrups Made of Normal Strength and High Strength Concretes. *Advances in Structural Engineering*. 2010;13(1):29–41.

22. Hasgul U, Yavas A¸ Birol T, Turker K Steel Fiber Use as Shear Reinforcement on I-Shaped UHP-FRC Beams. *Applied Sciences*. 2019;9(24):1–17. https://doi.org/10.3390/app9245526

23. Islam MS, Pam HJ, Kwan AKH Shear Capacity of High-Strength Concrete Beams with their Point of Inflection within the Shear Span. *Proceedings of the Institution of Civil Engineers, Structures and buildings*. 1998;128(1):91–99. https://doi.org/10.1680/istbu.1998.30038

24. Johnson MK, Ramirez JA Minimum Shear Reinforcement in Beams with Higher Strength Concrete. *ACI Structural Journal*. 1989;86(4):376–382.

25. Kani MW, Huggins MW, Wittkopp PF *Kani on Shear in Reinforced Concrete*. Canada: University of Toronto; 1979.

26. Kim JK, Park YD Shear Strength of Reinforced High Strength Concrete Beams without Web Reinforcement. *Magazine of Concrete Research*. 1994;46:1–8. https://doi.org/10.1680/macr.1994.46.166.7

27. Kulkarni SM, Shah SP Response of Reinforced Concrete Beams at High Strain Rates. *ACI Structural Journal*. 1998;95(6):705–715.

28. Kwak Y-K, Eberhard MO, Kim W-S, Kim J Shear Strength of Steel Fiber-Reinforced Concrete Beams without Stirrups. *ACI Structural Journal*. 2002;99:530–538.

29. Mohammed MH Shear Behavior of Reactive Powder Concrete Beams with and without Coarse Aggregate. *Engineering, Materials Science*. 2018;2:86–90. https://doi.org/10.22060/ceej.2017.12210.5145

30. Morrow J, Viest IM Shear Strength of Reinforced Concrete Frame Members without Web Reinforcement. *ACI Journal*. 1957;28(9):833–869.

31. Mphonde AG, Frantz GC Shear Tests of High- and Low-Strength Concrete Beams Without Stirrups. *ACI Journal*. 1984;81(4);350–357.

32. Pansuk W, Nguyen T, Sato Y, Den Uijl JA, Walraven JC Shear Capacity of High Performance Fiber Reinforced Concrete I-beams. *Construction and Building Materials*. 2017;157:182–193. https://doi.org/10.1016/j.conbuildmat.2017.09.057

33. Perera R, Barchín M, Arteaga A, De Diego A Prediction of the Ultimate Strength of Reinforced Concrete Beams FRP-Strengthened in Shear Using Neural Networks. *Composites Part B: Engineering*. 2010;41(4):287–298. https://doi.org/10.1016/j.compositesb.2010.03.003

34. Reddy LS, Rao NV, Rao TD Shear Response of Fibrous High Strength Concrete Beams without Web Reinforcement. *Civil Engineering Dimension*. 2011;13(1):50–58.

35. Salandra MA, Ahmad SH Shear Capacity of Reinforced Lightweight High-Strength Concrete Beams. *ACI Journal*. 1989;86(6):697–704.

36. Tavio T Experimental Investigation on Size Effect in Shear of High-Strength Concrete Beams. *The Journal for Technology and Science*. 2009;20(1):11–23. https://doi.org/10.12962/j20882033.v20i1.131

37. Thiemicke J, Fehling E Experimental and Numerical Investigations on I-Shaped UHPC-Beams with Combined Reinforcement under Shear Load. In book: *Insights and Innovations in Structural Engineering, Mechanics and Computation.* 1st Edition. 2016. P. 1363–1367.

38. Thorenfeldt E, Drangsholt G Shear Capacity of Reinforced High Strength Concrete Beams. *ACI 2nd International Symposium on HSC, ACI SP 121.8*. 1990. P. 129–154.

39. Yavas A, Goker CO Impact of Reinforcement Ratio on Shear Behavior of I-Shaped UHPC Beams with and without Fiber Shear Reinforcement. *Materials*. 2020;13(7):1–17. https://doi.org/10.3390/ma13071525

40. Xie Y, Ahmad SH, Yu T, Hino S, Chung W Shear ductility of reinforced concrete beams of normal and high strength concrete. *ACI Journal*. 1994;91(2):140–149.

41. Yoon Y-S, Cook WD, Mitchell D Minimum Shear Reinforcement in Normal, Medium and High-Strength Concrete Beams. *ACI Structural Journal*. 1996;93(5):576–584.

42. Lee J-H, Hong S-G Shear Strength of Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) I-shaped Beams without Stirrup. *Journal of the Korea Concrete Institute*. 2017;29:53–64. https://doi.org/10.4334/JKCI.2017.29.1.053

43. Magureanu C, Sosa I, Negrutiu C, Heghes B Bending and Shear Behavior of Ultra-high Performance Fiber Reinforced Concrete. *High Performance Structures and Materials V.* 2010;112:79–89. https://doi.org/10.2495/HPSM100081

44. Meszoly T, Randl N Shear Behavior of Fiber-Reinforced Ultra-High Performance Concrete Beams. *Engineering Structures*. 2018;168:119–127. https://doi.org/10.1016/j.engstruct.2018.04.075

45. Telleen K, Noshiravani T, Galrito R, Brühwiler E Experimental Investigation into the Shear Resistance of a Reinforced UHPFRC Web Element. In: *8th fib PhD Symposium in Kgs*. Lyngby; 2010. P. 1–6. URL: https://www.researchgate.net/publication/49461300_Experimental_investigation_into_the_shear_resistance_of_a_reinforced_UHPFRC_web_element (accessed: 04.03.2025).

46. Ţibea C, Bompa DV Ultimate Shear Response of Ultra-High-Performance Steel Fibre-Reinforced Concrete Elements. *Archives of Civil and Mechanical Engineering*. 2020;20(49):1–16.

47. Wu X, Han S-M First Diagonal Cracking and Ultimate Shear of I-Shaped Reinforced Girders of Ultra-high performance fiber reinforced concrete without stirrup. *International Journal of Concrete Structures and Materials*. 2009;3:47–56. https://doi.org/10.4334/IJCSM.2009.3.1.047

48. Yang I-H, Joh C, Kim B-S Shear Behaviour of Ultra-High-Performance Fibre-Reinforced Concrete Beams Without Stirrups. *Magazine of Concrete Research*. 2012;64(11):979–993.

49. Zagon R, Matthy S, Kiss Z Shear behaviour of SFR-UHPC I-shaped beams. *Construction and Building Materials*. 2016;124:258–268. https://doi.org/10.1016/j.conbuildmat.2016.07.075

50. Lee JW, Joh C, Choi ES, Kwak IJ, Kim BS Estimation of Shear Behavior of Ultra High Performance Concrete I Girder without Shear Stirrups. *Key Engineering Materials*. 2013;525–526:557–560. https://doi.org/10.4028/www.scientific.net/KEM.525-526.557

51. Qi J, Ding X, Wang Z, Hu Y Shear Strength of Fiber-Reinforced High-Strength Ssteel Ultra-High-Performance Concrete Beams Based on Refined Calculation of Compression Zone Depth Considering Concrete Tension. *Advances in Structural Engineering*. 2019;22:2006–2018. https://doi.org/10.1177/1369433219829805

About the Authors:

Murat M. Tamov, Cand.Sci. (Eng.), Associate Professor of the Department of Building Structures of Kuban State Technological University (2 Moskovskaya str., Krasnodar, 350072, Russian Federation), ORCID, murat.tamov@gmail.com

Olga V. Rudenko, Cand.Sci. (Eng.), Associate Professor of the Department of Computing Technologies of Kuban State University (149 Stavropol Street, Krasnodar, 350040, Russian Federation), ORCID, olga_ned@mail.ru

Mina I.F. Salib, Engineer of the Department of Building Structures of Kuban State Technological University (2 Moskovskaya str., Krasnodar, 350072, Russian Federation), ORCID, minaibrahim1234@yahoo.com

Claimed Contributorship:

MM Tamov: scientific supervision, development of the main concept, formulation of the research goals and objectives, formulation of conclusions, and text editing.

OV Rudenko: assistance and guidance in using the modeling software and analyzing the results, text preparation.

MIF Salib: conducting experimental research and analyzing the results, performing calculations, searching, analyzing, and systematizing data, compiling the list of references.

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

All authors have read and approved the final manuscript.

Об авторах:

Мурат Мухамедович Тамов, кандидат технических наук, доцент кафедры строительных конструкций Кубанского государственного технологического университета (350072, Российская Федерация, г. Краснодар, ул. Московская, 2), ORCID, murat.tamov@gmail.com

Ольга Валентиновна Руденко, кандидат технических наук, доцент кафедры вычислительных технологий Кубанского государственного университета (350040, Российская Федерация, г. Краснодар, ул. Ставропольская, 149), ORCID, olga_ned@mail.ru

Салиб Мина Ибрахим Фахми, инженер кафедры строительных конструкций Кубанского государственного технологического университета (350072, Российская Федерация, г. Краснодар, ул. Московская, 2), ORCID, minaibrahim1234@yahoo.com

Заявленный вклад авторов:

М.М. Тамов: научное руководство, формирование основной концепции, цели и задачи исследования, формулировка выводов, корректировка текста.

О.В. Руденко: помощь и руководство по использованию программы моделирования и анализу результатов, подготовка текста.

М.И.Ф. Салиб: проведение экспериментальных исследований и анализ их результатов, проведение расчетов, поиск, анализ и систематизация данных, формирование списка литературы.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 22.02.2025
Reviewed / Поступила после рецензирования 14.03.2025
Accepted / Принята к публикации 02.04.2025

BUILDING CONSTRUCTIONS, BUILDINGS AND ENGINEERING STRUCTURES

СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ, ЗДАНИЯ И СООРУЖЕНИЯ

Check for updates

Original Empirical Research

UDC 699.841
https://doi.org/10.23947/2949-1835-2025-4-2-21-37

EDN: YPWWOY

Evaluation of the Reliability of Design Solutions during the Reconstruction of a Cultural Heritage Site Taking into Account Seismic Impacts

Khasan N. Mazhiev[1] ✉, **Kazbek Kh. Mazhiev**[1,2], **Yuri V. Panasenko**[3], **Amina Kh. Mazhieva**[1], **Aslan Kh. Mazhiev**[1,4], **Adam Kh. Mazhiev**[4]

[1] Millionshchikov Grozny State Oil Technical University Academy of Sciences of the Chechen Republic, Grozny, Russian Federation
[2] Kh. Ibragimov Complex Institute of the Russian Academy of Sciences, Grozny, Russian Federation
[3] Central Research Institute of Building Structures named after V. A. Kucherenko JSC "Research Center "Construction", Moscow, Russian Federation
[4] Academy of Sciences of the Chechen Republic, Grozny, Russian Federation
✉ seismofund@mail.ru

Abstract

Introduction. In order to ensure seismic resistance and reduce seismic loads, during the reconstruction of the cultural heritage site, a spatial calculation of the supporting structures of the cinema and variety hall was performed. This article analyzes the structural system, the calculation and dynamic model taking into account the main and special combinations of loads.

Materials and Methods. The calculations were carried out using the analytical method and the finite element method in the STARK ES software package.

Results. For the purpose of reconstructing the building of the cultural heritage site, the results of dynamic calculation were obtained for the main and special combinations of loads and corresponding combinations of internal forces in the calculated structures of the cinema and variety hall. In this case, only 25 loadings were used.

Discussion and Conclusions. The results of the calculation of the cinema building showed that the required load-bearing capacity of the building of a cultural heritage site is ensured in the considered design situation.

Keywords: building, reconstruction, seismic impact, calculation, load, structural system, seismic resistance, calculation-dynamic model

For citation: Mazhiev HN, Mazhiev KH, Panasenko YuV, Mazhieva AH, Mazhiev AH, Mazhiev AH. Evaluation of the Reliability of Design Solutions during the Reconstruction of a Cultural Heritage Site Taking into Account Seismic Impacts. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):21–37. http://doi.org/10.23947/2949-1835-2025-4-2-21-37

Оригинальное эмпирическое исследование

Оценка надежности конструктивных решений при реконструкции объекта культурного наследия с учетом сейсмических воздействий

Х.Н. Мажиев[1] ✉, **К.Х. Мажиев**[1,2], **Ю.В. Панасенко**[3], **А.Х. Мажиева**[1], **А.Х. Мажиев**[1,4], **А.Х. Мажиев**[4]

[1] Грозненский государственный нефтяной технический университет имени академика М.Д. Миллионщикова, г. Грозный, Российская Федерация

[2] Комплексный научно-исследовательский институт им. Х.И. Ибрагимова Российской академии наук, г. Грозный, Российская Федерация

[3] Центральный научно-исследовательский институт строительных конструкций имени В.А. Кучеренко АО «НИЦ «Строительство», г. Москва, Российская Федерация

[4] Академия наук Чеченской Республики, г. Грозный, Российская Федерация

✉ seismofund@mail.ru

Аннотация

Введение. С целью обеспечения сейсмостойкости и снижения сейсмических нагрузок при реконструкции объекта культурного наследия выполнен пространственный расчет несущих конструкций сооружений кино-эстрадного зала. В настоящей статье анализируются конструктивная система, расчетно-динамическая модель с учетом основных и особых сочетаний нагрузок.

Материалы и методы. Расчеты проводились аналитическим методом и методом конечных элементов в программном комплексе STARK ES.

Результаты исследования. Получены результаты динамического расчета при основных и особых сочетаниях нагрузок и соответствующих сочетаниях внутренних усилий в рассчитываемых конструкциях сооружений реконструируемого объекта (кино-эстрадного зала). При этом было использовано всего 25 загружений.

Обсуждение и заключение. Результаты расчета здания кинотеатра показали, что обеспечивается требуемая несущая способность здания объекта культурного наследия при рассматриваемой расчетной ситуации.

Ключевые слова: здание, реконструкция, сейсмическое воздействие, расчет, нагрузка, конструктивная система, сейсмостойкость, расчетно-динамическая модель

Для цитирования. Мажиев Х.Н., Мажиев К.Х., Панасенко Ю.В., Мажиева А.Х., Мажиев А.Х., Мажиев А.Х. Оценка надежности конструктивных решений при реконструкции объекта культурного наследия с учетом сейсмических воздействий. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):21–37. https://doi.org/10.23947/2949-1835-2025-4-2-21-37

Introduction. When there is renovation work occurring in cities, it is essential that cultural heritage sites that were designed taking into account old norms and calculation models are preserved.

To this end, the task is to conduct a spatial calculation of the load-bearing building structures of the cinema and variety hall of the cinema theatre to assess their reliability during reconstruction. The reconstructed building is a cultural heritage site and is in a seismically active area. [1–5, 14].

There must be scientific and technical assessment of the compliance of design solutions in compliance with the requirements of regulatory documents of the Russian Federation on building safety, as well as the development of recommendations for the design stage of "working documentation", accounting for possible changes in the design scheme of the structural model of the building during reconstruction.

Materials and Methods. The structural system being investigated is a trapezoidal cinema building, framed, with exterior side walls made of concrete blocks and bricks and with stained glass windows on the southern (main) and northern facades. The cinema theatre is made up of two halls: a large one with 1,200 seats and a small one with 80 seats. The cinema theatre is located on the stylobate. Most of the building is taken up by an audience hall with a widescreen screen and an amphitheater for seating.

The cinema theatre building is made up of two components (Fig. 1):

– administrative wing, in the axes 4–11/D–F;

– audience hall, in the axes 1–14/A–D, and the basement, in the axes Iп–IIп/C–F.

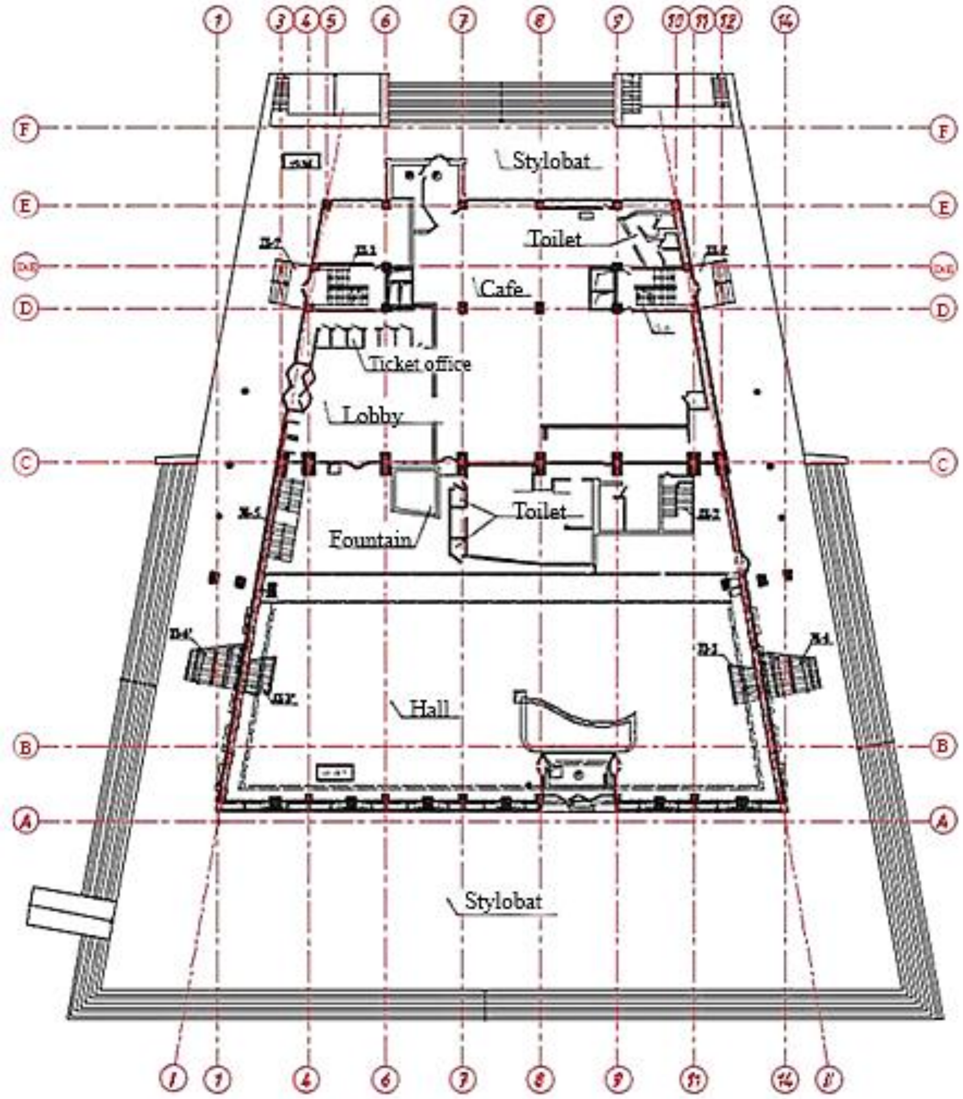


Fig. 1. Layout scheme of the building [14]

The administrative wing of the building is made of 4 storeys, the structural scheme is a monolithic reinforced concrete frame frame with a crossbar arrangeme+nt. Prefabricated hollow slabs laid along digital axes were used as elements of the interstory floors (coatings). The external wall filling of the frame is made in the form of lightweight ceramic brick masonry.

The audience hall of the building is 2-storied. The supporting elements are the frames installed along the digital axes of the building. The structural elements of the frame are reinforced concrete and inclined metal racks, reinforced concrete inclined crossbar and console with a span of 11.66 m. The reinforced concrete frame elements have a variable cross-section. The junction of the metal rack and the inclined bolt is hinged. A reinforced concrete tightening is provided to make up for the horizontal forces generated in the support unit of the metal rack. The support unit of the metal rack is hinged, the reinforced concrete rack is rigid. Precast reinforced concrete hollow slabs were used as the floor elements of the 1st floor. In order to ensure the spatial rigidity of the frames, monolithic reinforced concrete struts R-1 and R-2 were made at the top of the struts along the axes "A" and "C", precast reinforced concrete cross ties were installed along their entire length with a step of 5-6 m [1–5, 14].

Metal beams of a composite I-beam section with a height of 1.7 m were used as supporting structures of the coating. The console with a span of 11.66 m is supported along the "A" axis by an inclined metal rack of the supporting frame through a metal rack Ст-1 supported by a monolithic reinforced concrete strut P-1, along the "D" axis by columns of the frame of the administrative wing of the building. The spatial stability of the load-bearing elements of the coating is ensured by the presence of vertical metal bracing trusses, horizontal struts and cross ties installed along the upper and lower girder belts. The coating structures are precast reinforced concrete ribbed slabs.

Prefabricated blocks made of expanded clay concrete not connected to the columns of the frame were used as enclosing structures (exterior walls) of the main part of the building.

Transitional galleries at the 3rd floor level are provided in the axes I/A–D and II/A–D of the audience hall for communication between the camera room and the administrative wing of the building (Fig. 1).

The reconstruction project involves preservation of the spatial appearance of the building as part of the adaptation to modern use for concert events. According to the reconstruction project, existing structures are to be partially dismantled and later restored and the preserved structures are to be reinforced [6–11].

According to the architectural concept of the reconstruction of the facility, it is planned to build a developed underground basement around the cinema theatre for more modern functionality and to expand recreational opportunities in terms of the location of blocks C1–C5 around block A1 with a functional connection between the buildings (Fig. 2).

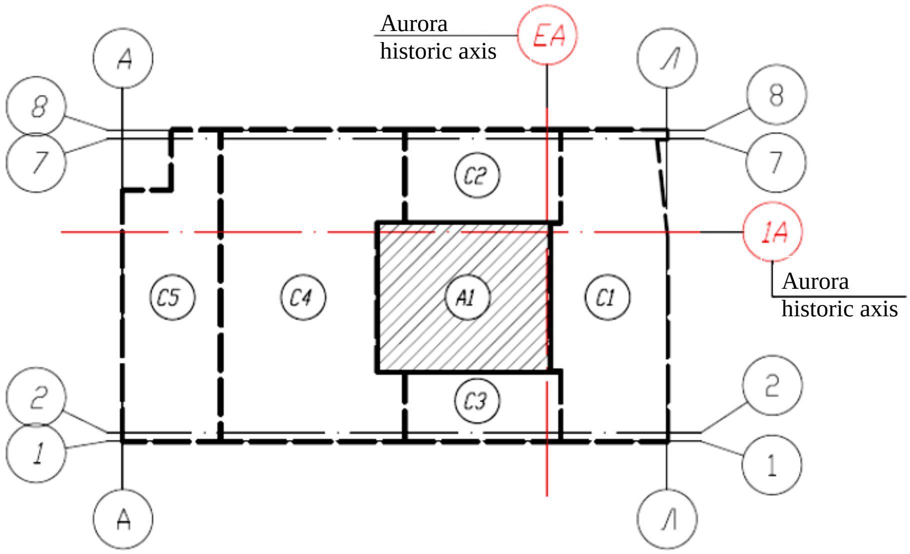


Fig. 2. Situational scheme of the area

The following structural and spatial planning measures are seen as part of the reconstruction of the main building:

– expanding the audience hall due to the space of the administrative wing. To this end, in the latter, some of the frame is to be dismantled from the basement to the 4th floor (columns, beams, ceilings, basement walls, curtain walls) with the construction of a new frame and the installation of two reinforced concrete beams covering the hall with a span of 21.1 m and 18.3 m. In order to support the beams of the coating, two stiffness cores are performed in axes 4–6/D–E and 9–11/D–E with pilaster columns for the projected beams;

– the existing internal stairwells are to be dismantled. Evacuation stairwells are built inside the projected rigidity cores;

– the existing stylobate part of the administrative block in the axes is to be dismantled and rebuilt. $I_{п}$–I, $II_{п}$–II, E–F;

– the V-shaped beams of the auditorium B-1.1 are preserved with their reinforcement according to the calculation;

– the audience hall is undergoing reconstruction of the existing technological galleries and two levels of projected balconies are being installed along the side walls of the building. Balconies and galleries are supported by projected columns mounted on V-shaped beams. Balconies and galleries are made in a steel frame to reduce the weight. Recessed columns are installed in the existing exterior wall of the building to support balconies and galleries;

– the existing exterior walls of the audience hall along axes I and II are to be reconstructed and reinforced with concrete pilaster columns;

– the existing foundations are reinforced by installing additional borehole injection piles and reinforced cement elements around the perimeter;

– new pile foundations are to be built for the projected load-bearing structures;

– an underground gallery is to be built for a passage under the cinema building between the attached museum and cinemas on the southern side, and a cafe on the northern side.

The following measures are provided in order to reduce the load on the building:

– dismantling of the existing floors and partitions with the installation of modern lightweight materials — drywall and gypsum fiber sheet, aerated concrete blocks of autoclave hardening;

– dismantling of the hall floor covering (including prefabricated reinforced concrete slabs that fail to comply with the requirements for coatings in seismic areas according to the survey results) with the installation of a lightweight membrane coating on a profiled sheet;

– dismantling of the existing galleries along the hall with the installation of new galleries, ceilings and balconies on steel beams and columns;

– dismantling of the curtain walls of the administrative wing with the installation of earthquake-resistant curtain walls made of aerated concrete blocks of autoclave hardening.

For possibly installing an attached underground part and protecting the reconstructed building, a wall in the ground (tongue–and-groove fencing) with a thickness of 600–800 mm is installed along the perimeter of the reconstructed building and along the perimeter of the attached underground space with a spacer system made of steel pipes and anchoring on two to four levels. The spacer system is dismantled as the underground part is built and the wall is supported in the ground on the frame of the projected stylobate.

The existing pile foundations are reinforced with borehole injection piles to transfer loads from existing foundations to dense sands at the base of the building and the possibility of hanging existing foundations accounting for the arrangement of the attached underground part below the tip of the existing piles [12–15].

In order to bring the building to the requirements of seismic standards, the lobby block with the audience hall and the former administrative wing are combined into a single seismic compartment. The projected rigidity cores of the administrative part are included in the operation of the main lobby — audiencer hall seismic unit. With this solution, the beams of the coating are supported by a combined seismic unit.

Individual elements of columns and beams with insufficient load-bearing capacity are also structurally reinforced according to the calculations for the main and special combination of the loads.

The steel elements of the inclined columns of the main lobby are reinforced according to the calculation. The support points of the inclined columns are reinforced as rigid ones.

The roof beams of the audience hall B1 are preserved and reinforced according to the calculation. Dismantling the frame of the administrative wing involves re-supporting the roof beams on temporary supports installed along the axis C. After dismantling and erecting the projected administrative part of the newly designed beams along the axis, the existing metal beams are re-supported on them. There is reconstruction of the support joint of the beams along the D axis.

The cantilever trusses along the I, II axes are dismantled and rebuilt attached to the built–in wall frame along the I, II axis. The communication system in the canopy in the A1–A/B axes is to be replaced.

The elements of reinforced concrete structures with defects identified during the examination are restored and reinforced according to the calculation.

External escape ladders are to be dismantled and rebuilt in monolithic reinforced concrete on the projected stylobate. The existing staircase in the foyer is to be retained and reinforced.

In order to assess the reliability of the design solutions employed in the project, a verification calculation of the spatial model of the structure for design loads and impacts was performed. The calculation was performed using the STARK ES software package.

A spatial shell-rod model was used as a computational model where the supporting columns, crossbars and truss elements are represented by general rod elements, the coating shell, floor slabs and walls are represented by elements of a flat shell (Fig. 3).

The elements of the built–in rooms in axes C–D/1–3, C–D/7–11, C–D/15–18 and the roof extensions in axes A1–A/7–13 are specified only for collecting and transferring the load to the load-bearing elements of the frame.

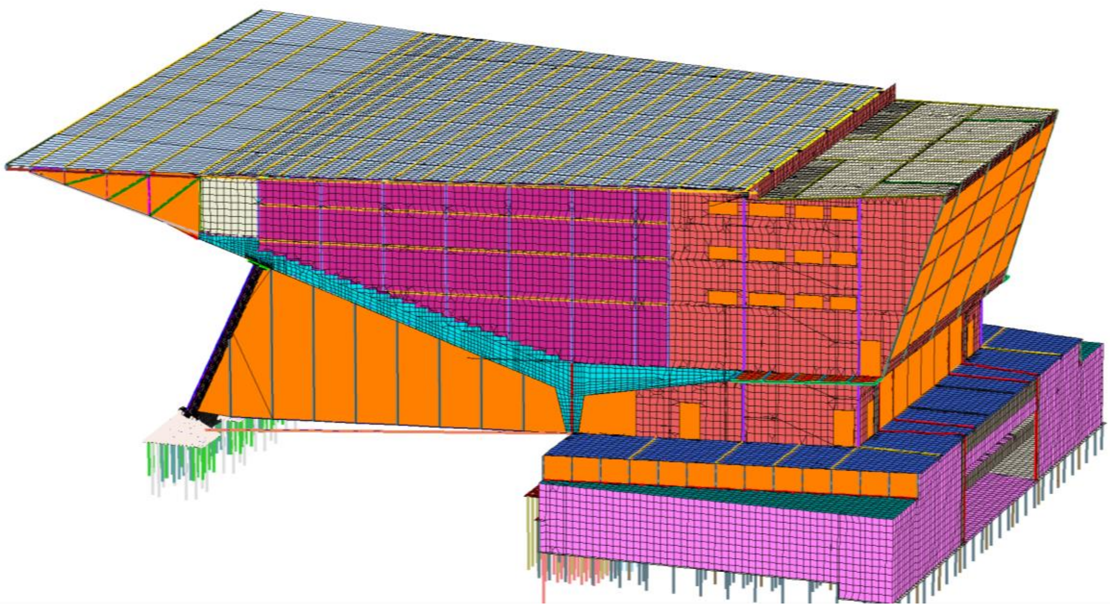


Fig. 3. Finite-element model of the cinema hall (block A1) [14]

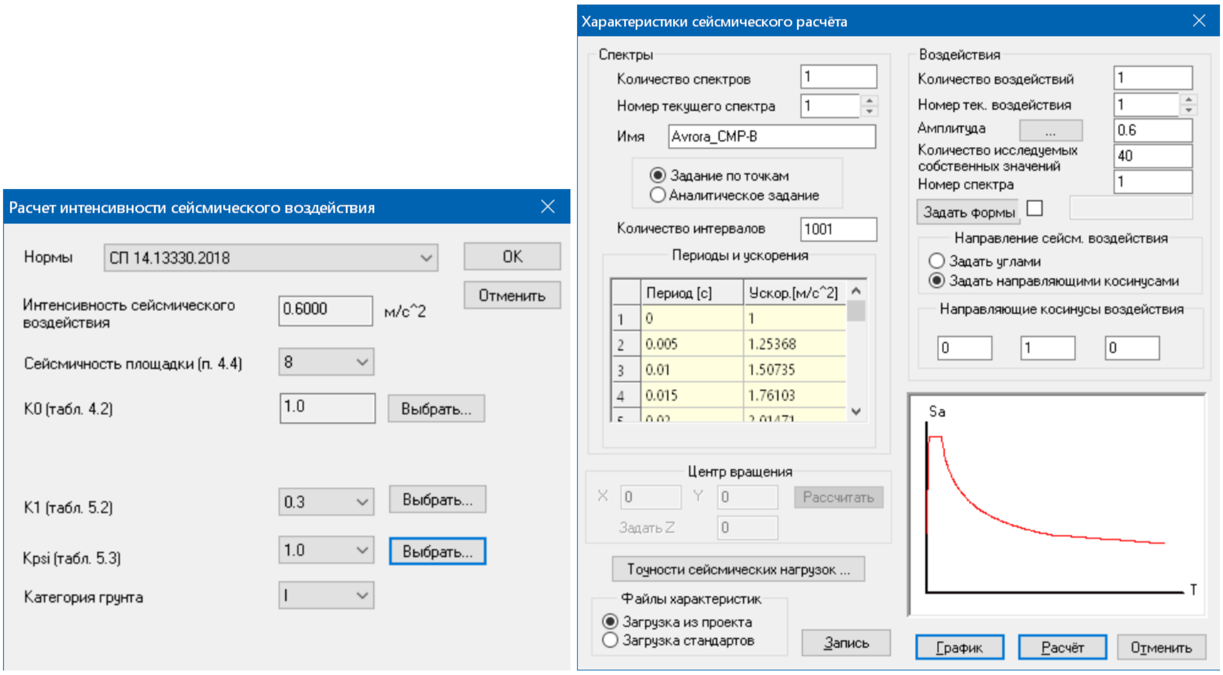
While calculating the building, the following loads and impacts were accounted for:
– vertical constant loads from the own weight of load-bearing and enclosing structures;
– long-term loads from engineering equipment;
– temporary loads on floors and coatings;
– snow load;
– average and pulsation components of the wind load;
– seismic impact on the structure;
– special emergency impacts as a special combination of loads accounting for extreme climatic influences.

The normalized parameters and conditions of the construction object are shown in Table 1. Fig. 4 shows the values of the parameters for calculating the seismic impact.

Table 1

Standardized parameters and conditions of the construction object

Name	**Value**	**Normative document, section**
The level and class of responsibility of the facility, the reliability coefficient in terms of responsibility	Normal, КС–2	№ 190-FL, section 48.1 № 384-FL
The value of the reliability coefficient for the responsibility of the facility, γ_n	1,0	GOST 27751-2014
Wind load: – wind area; – standard value of wind pressure, kPa.	IV 0,48	SP 20.13330.2016
Snow load: – snow area; – normative value of the snow cover weight, kPa.	II 1,1	SP 20.13330.2016
Climatic area/subarea	III/IIIБ,	SP 131.13330.2020
Гололедная нагрузка	III 10 mm	SP 20.13330.2016
Seismicity of the construction area – map A – map B	7 points 8 points	Seismic microzoning



a) *b)*

Fig. 4. Parameter values for calculating the seismic impact: *a* — calculation of seismic impact intensity; *b* — characteristics of the seismic calculation

A total of 25 downloads was used in the calculated model of the cinema hall to account for all the loads. Fig. 5–6 shows the schemes for applying wind loads in the +*X* and +*Y* directions, respectively.

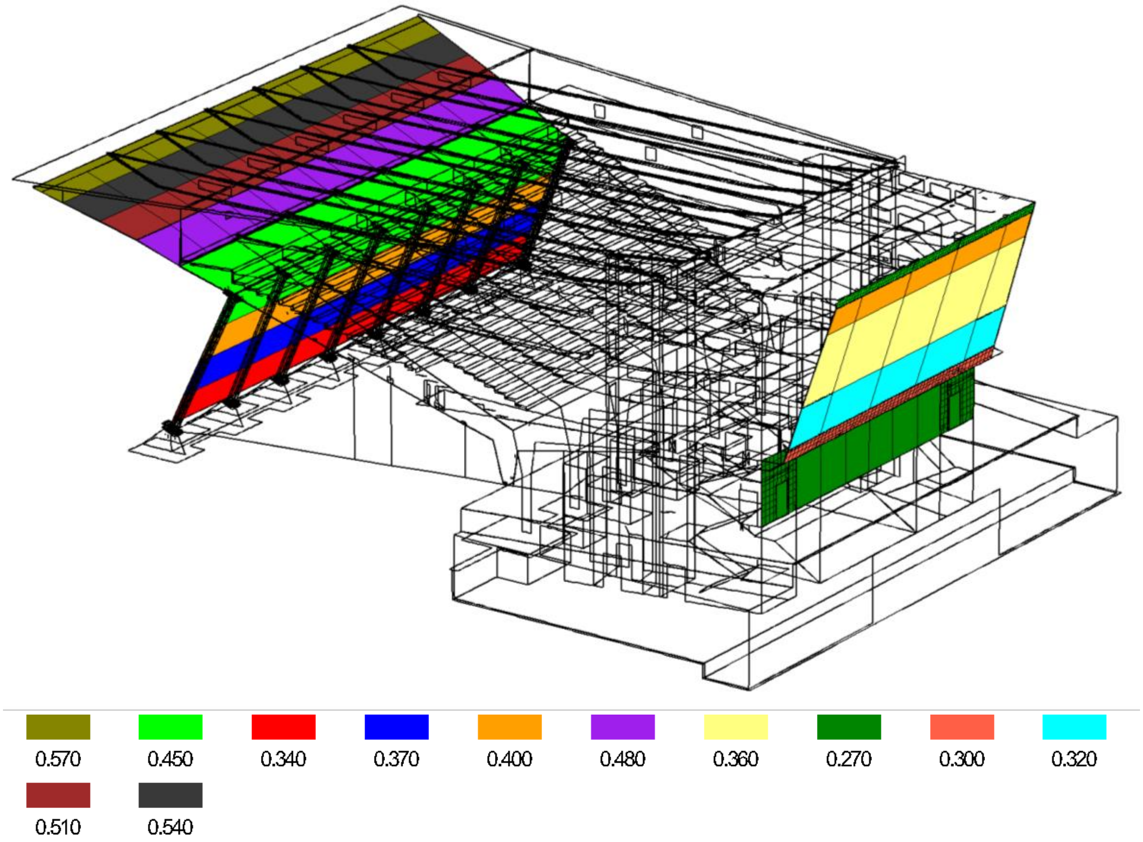


Fig. 5. Wind load application scheme. Direction +*X*, kN/m^2 [14]

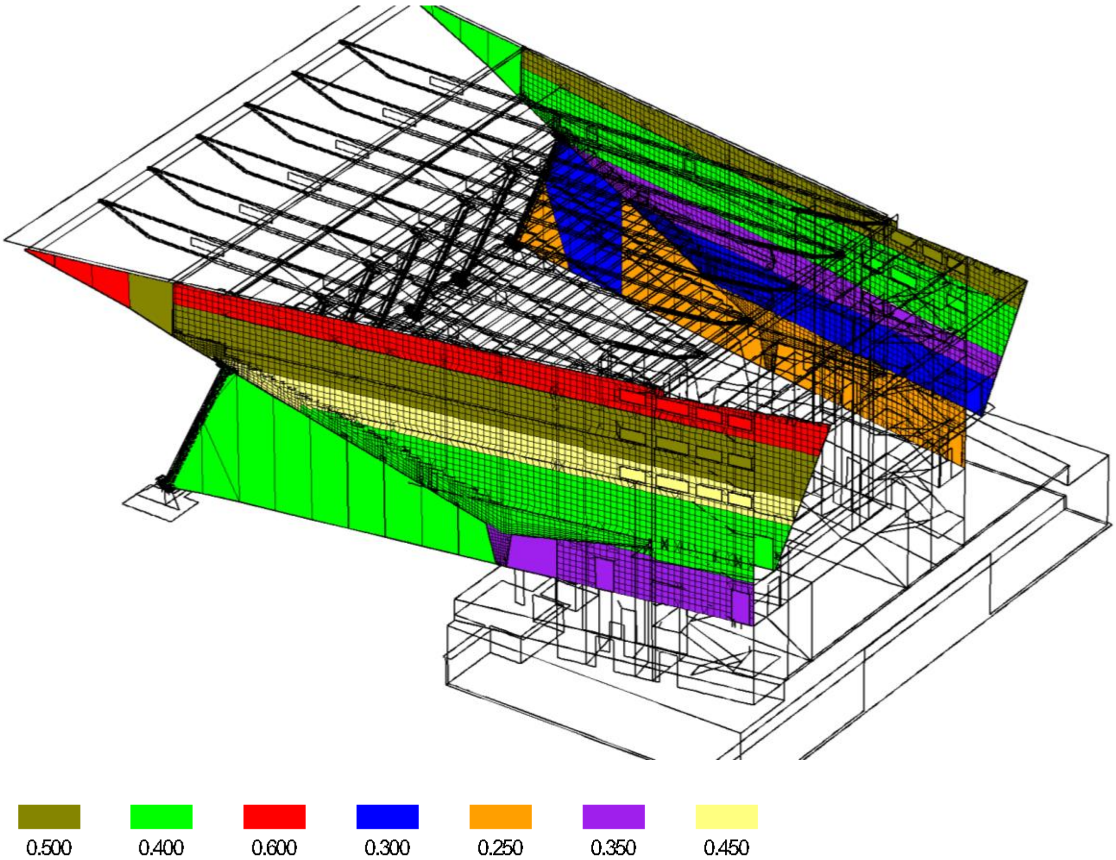


Fig. 6. Wind load application scheme. Direction +*Y*, kN/m^2 [14]

Research Results. The foundation sediment was evaluated for the main combinations of the full values of the standard loads. The foundation sediment is shown in Fig. 7. The maximum precipitation was 12.4 mm.

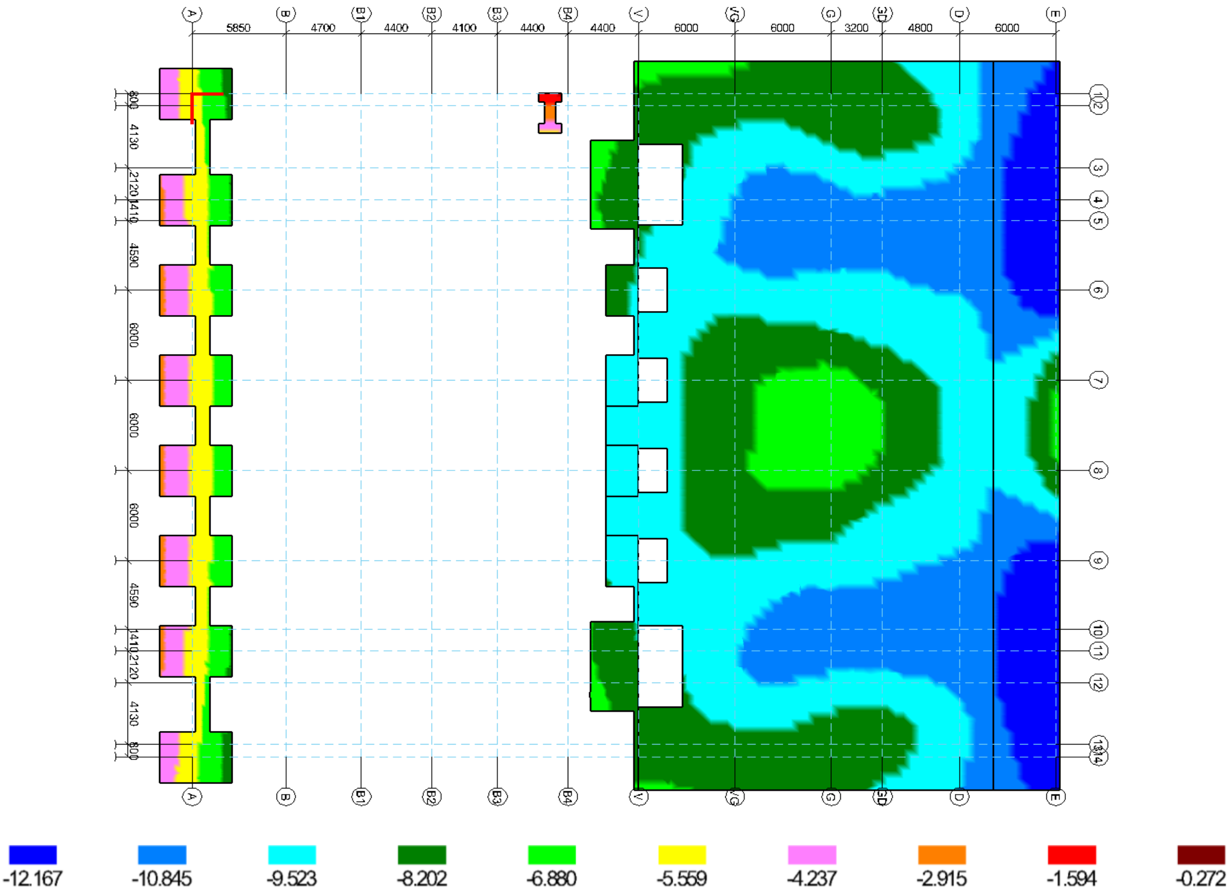


Fig. 7. Sediment of the foundation *Uz* [14]

The maximum value of the relative difference in the sediment from the main load combinations was $\Delta s/L$ = 0.00032, which is not over the permissible value of 0.004.

The horizontal deviations of the top of the building were evaluated for the main combinations of the full values of the standard loads (Fig. 8).

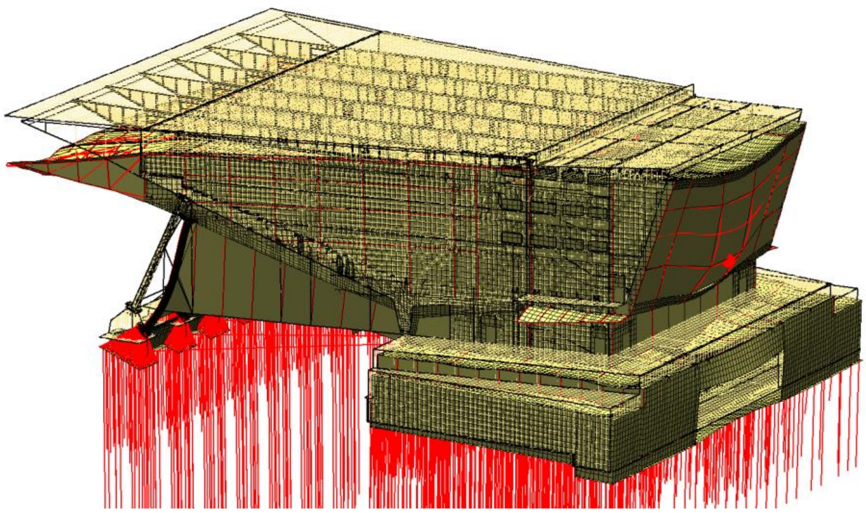


Fig. 8. Horizontal displacement of the top of the building [14]

The maximum horizontal displacement of the top of the building from the standard load values is 19.3 mm, which is not over the maximum permissible value of 36 mm.

The results of the calculation of the first form of stability loss and the corresponding critical load parameter P_{cr} are given in Fig. 9.

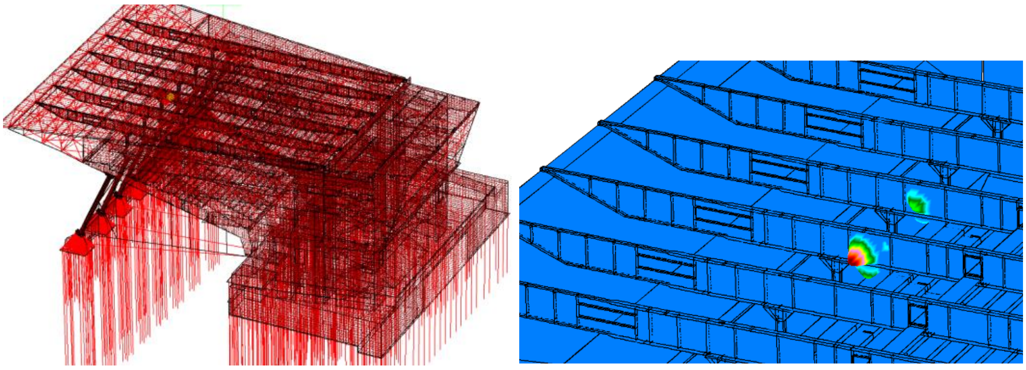
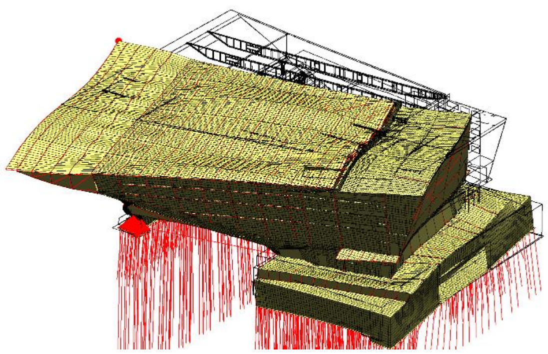


Fig. 9. Form 1 of the stability loss [14]

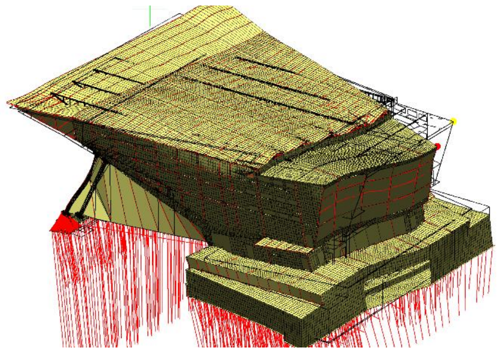
The lowest critical load parameter (stability margin) accounting for the reliability coefficient of responsibility is 1.56. The overall stability of the load-bearing structures of the building is ensured.

In order to enhance the reliability of the historical structures of the coating beams, it was recommended that the wall stability in the support zones to the value is increased to P_{cr} of no less than 2.0.

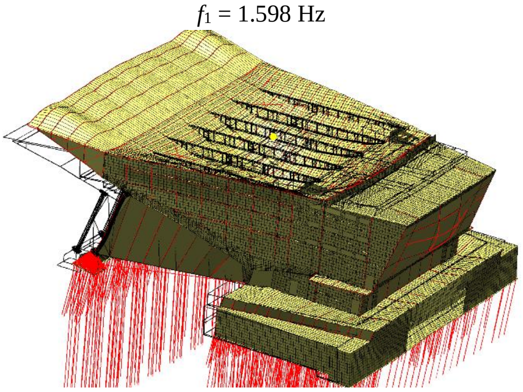
Fig.10 shows the first general forms of natural oscillations of the cinema hall.



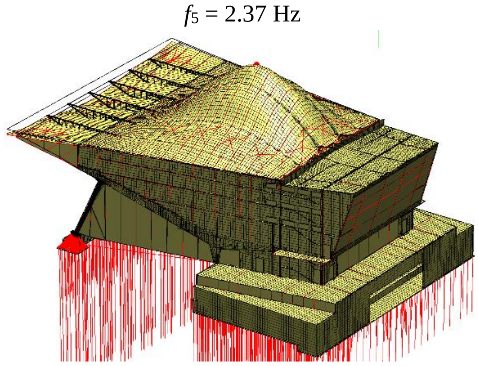
f_1 = 1.598 Hz



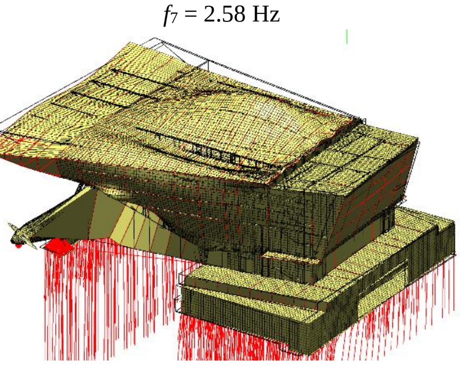
f_5 = 2.37 Hz



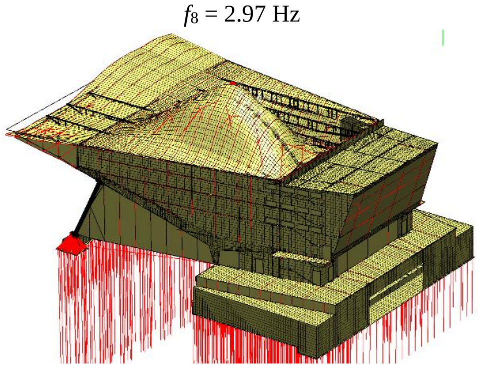
f_7 = 2.58 Hz



f_8 = 2.97 Hz



f_{10} = 3.06 Hz



f_{11} = 3.21 Hz

Fig. 10. Forms of own oscillations, block A1 [14]

The amount of reinforcement was calculated for the main load combinations, accounting for the conditions of strength and crack resistance. The material characteristics of reinforced concrete structures are shown in Table 2.

Table 2

Characteristics of structural materials

Structure	Concrete grade	Longitudinal reinforcement class	Transverse reinforcement class	Thickness of the protective layer			
				SO, mm	SU, mm	RO, mm	RU, mm
Foundation	B30	A500C	A240	50	80	80	50
V-beam B1.1 historic	B25	AII	AII	40	40	60	60
V-beam B1.1 reinforced shotcrete	B30	A500C	A240	20	20	45	45

The results of the selection of the necessary foundation reinforcement are in Fig. 11–14 below.

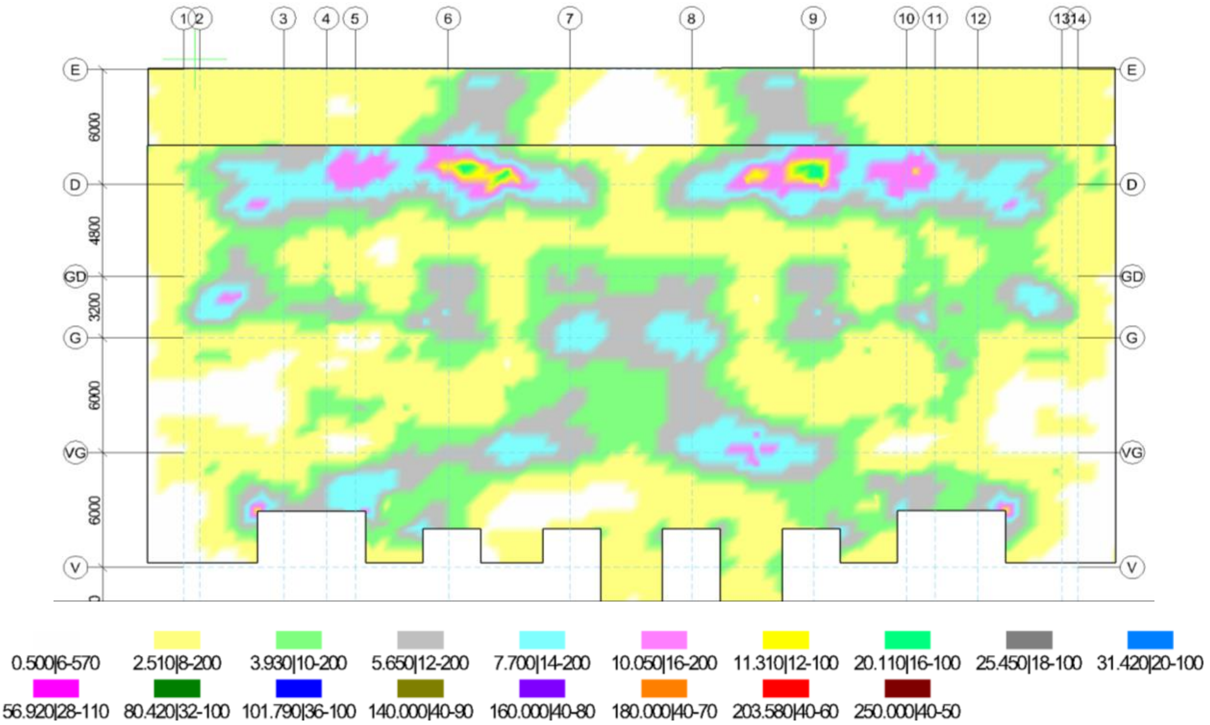


Fig. 11. Reinforcement of the foundation. Upper longitudinal reinforcement in the direction of the axis *R*, cm^2/m [14]

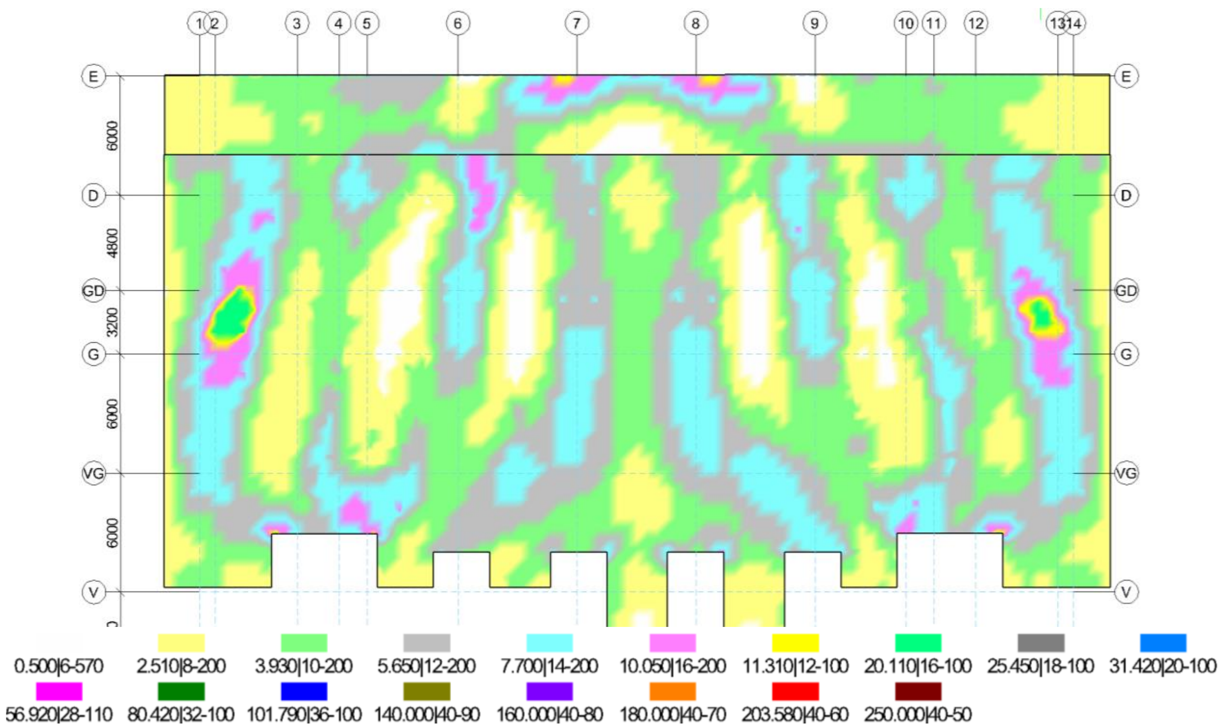


Fig. 12. Reinforcement of the foundation. Upper longitudinal reinforcement in the direction of the axis *S*, cm^2/m [14]

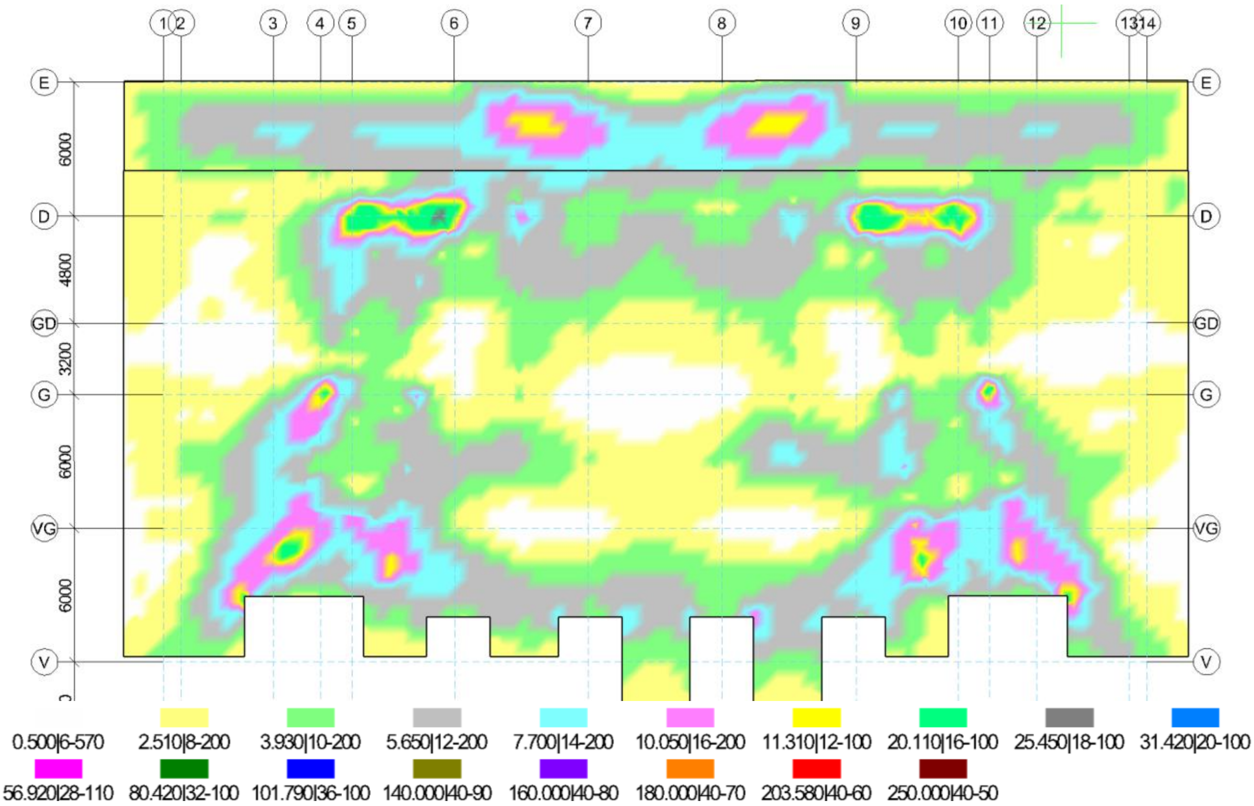


Fig. 13. Reinforcement of the foundation. Lower longitudinal reinforcement in the direction of the axis *R*, cm^2/m [14]

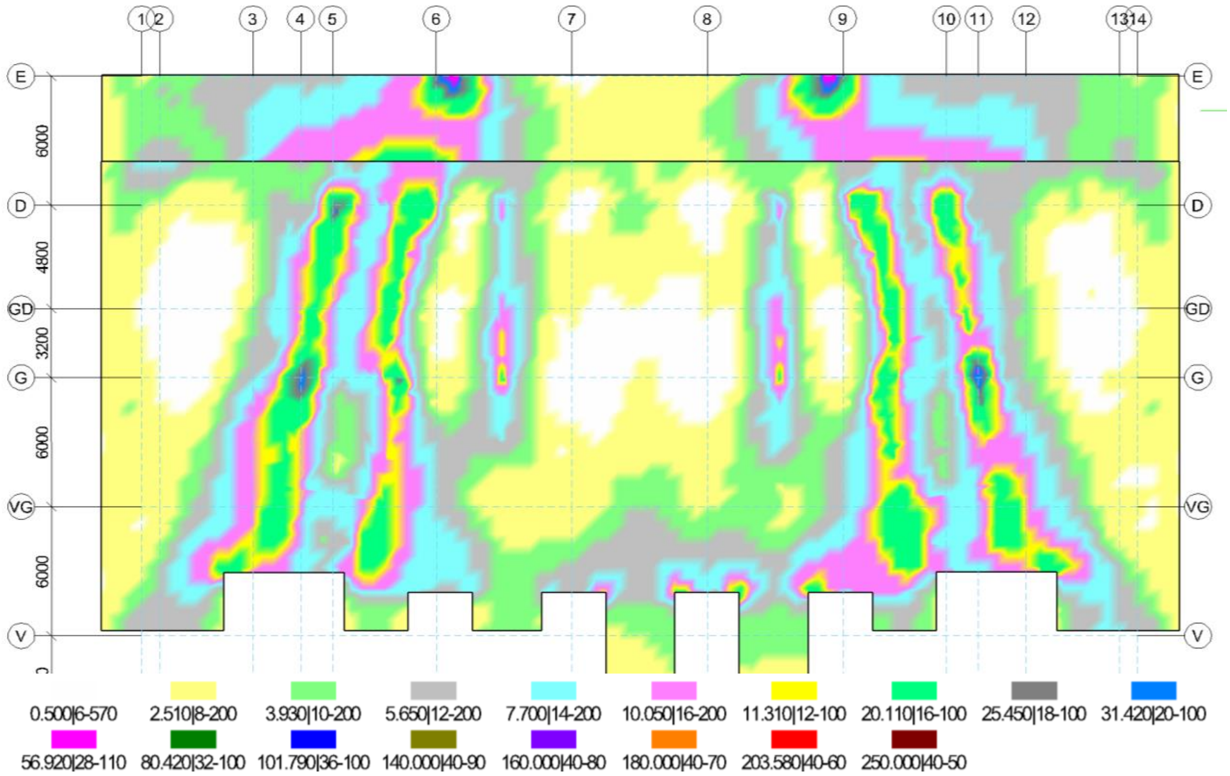


Fig. 14. Reinforcement of the foundation. Lower longitudinal reinforcement in the direction of the axis *S*, cm^2/m [14]

The required reinforcement of the existing V-beam is in Fig. 15–16.

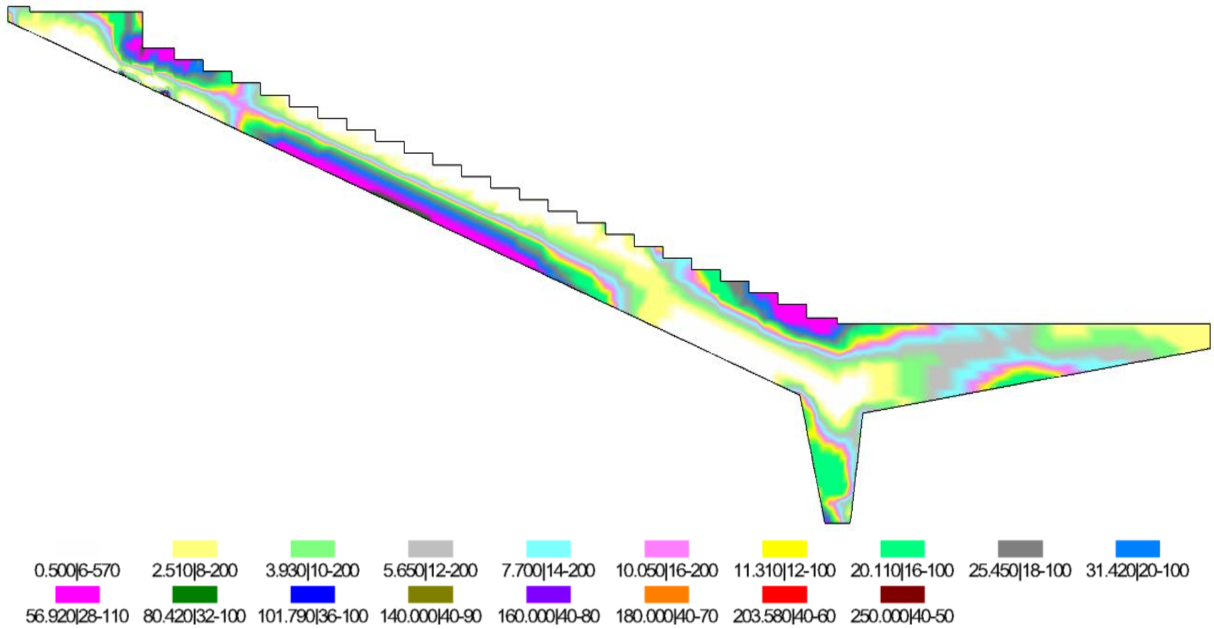


Fig. 15. Reinforcement of the existing V-beam. Upper and lower longitudinal reinforcement in the direction of the axis *R*, cm^2/m [14]

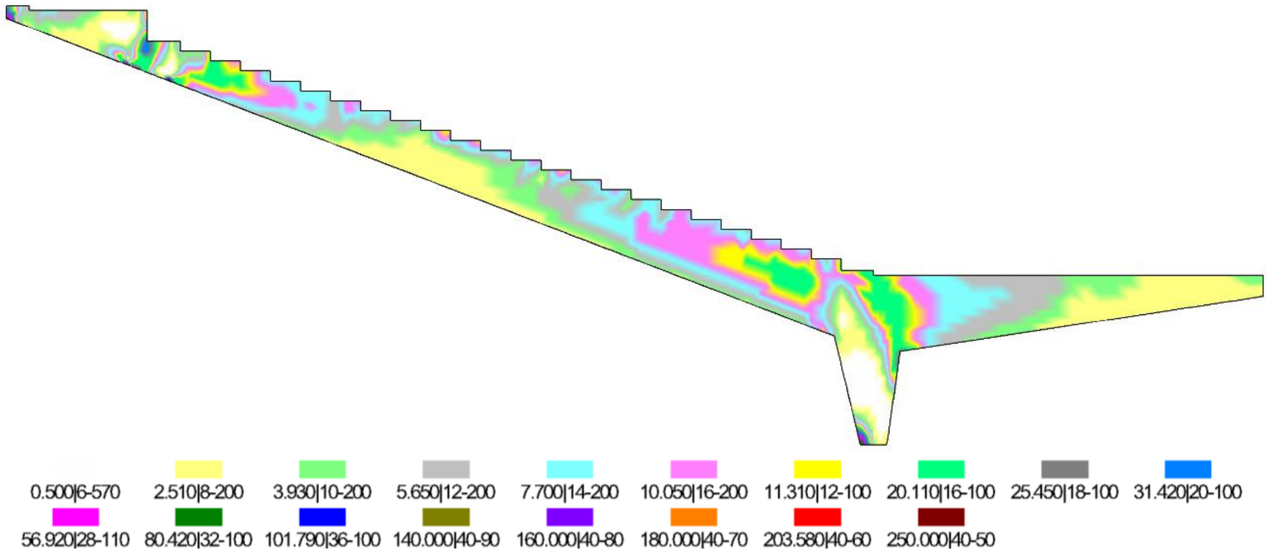


Fig. 16. Reinforcement of the existing V-beam. Upper and lower longitudinal reinforcement in the direction of the axis *S*, cm^2/m [14]

The stresses in the steel beams of the coating are estimated using the Huber-Mises strength theory for *min/max* superposition for a variety of combinations. The results are shown in Fig.17–18.

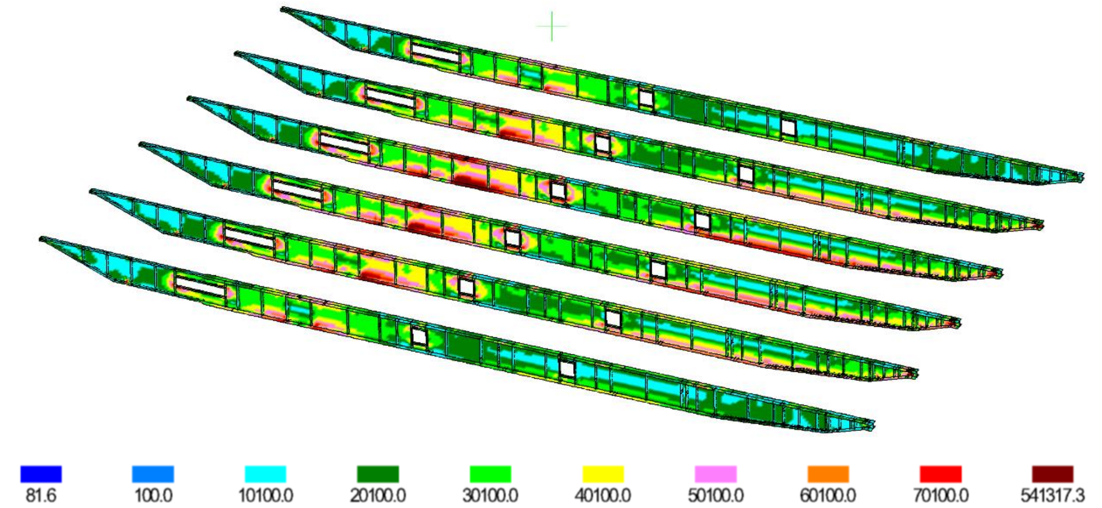


Fig. 17. Stresses in the steel beams of the coating for *min* superposition for a variety of combinations [14]

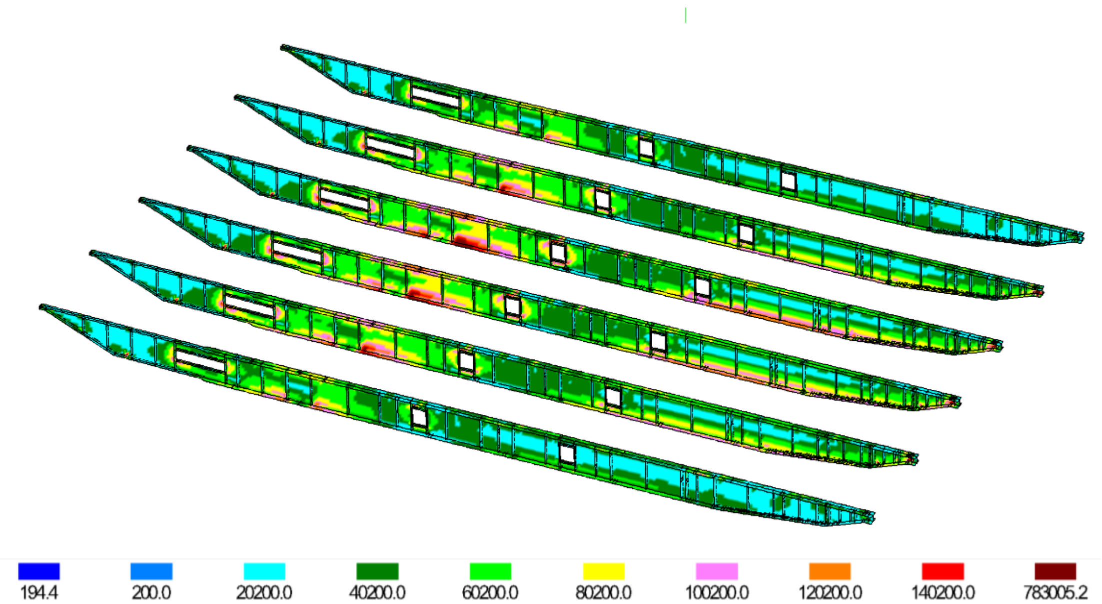


Fig. 18. Stresses in the steel beams of the coating for *max* superposition for a variety of combinations [14]

The load-bearing capacity of the elements of the coating beams in the A–C axes is provided for basic and special combinations of loads.

Results and Conclusion. As part of the calculations of the supporting structures of the cinema and variety hall (Block 1), the following was carried out:

1. Analysis of the project documentation and research materials.
2. Formation of a spatial design scheme of a building using a proven and certified STARK ES PC software package.
3. Collecting loads on structures based on the provided documentation accounting for the requirements of the standards.
4. Calculation of the shapes and frequencies of own vibrations of the structures.
5. Verification of the overall linear-elastic stability of the load-bearing system of the building for the main combinations of loads and impacts.
6. Inspecting the overall rigidity of the load-bearing system of the building, foundation sedimentation, and vertical plate deflections for major combinations of loads and impacts.
7. Calculation of the main elements of reinforced concrete and steel structures of a building according to the limiting conditions.

Based on the analysis of the results of the verification calculation of the load-bearing structures of the cinema hall under basic and special combinations of loads and impacts (accounting for the special loads from seismic impacts, fire trucks and emergency snow impacts), the following conclusions are made:

1. The overall rigidity and linear-elastic stability of the load-bearing system of the building are ensured.
2. The foundation sediment and horizontal displacement of the building structures are not over the limit values.
3. The stresses in the elements of steel structures are not over the design resistances of steel.
4. The amount of reinforcement in the reinforced concrete structures of the building should be assumed to be no less than that in the calculation results.

Hence the design solutions employed in the design of the cinema hall (block A1) ensure reliability, strength, rigidity and stability of load-bearing building structures under basic and special combinations of design loads and impacts.

While developing design documentation at the regulatory documentation stage, as well as during the construction, it is recommended that:

1. Tests of facade structures are performed in order to verify design solutions and validate mechanical safety.
2. Regulatory documentation is developed for reinforcing the steel beams of the coating, accounting for all of the stages of installation (dismantling) of structures based on appropriate calculations. It is necessary to allow for possible changes in the design scheme of the beam and that in the scheme of loosening the belt structures and walls.
3. Scientific and technical support is provided during the development of reinforcement of reinforced concrete V-beams of stands at the regulatory documentation stage and during the production of works. While calculating the reinforcement, it is necessary to account for the stages of installation and the joint work of the old and new material, as well as the requirements for the fire resistance of structures.

References

1. Themelis S. *Pushover Analysis for Seismic Assessment and Design of Structures*. Heriot-Watt University, School of the Built Environment, 2008. URL: https://www.ros.hw.ac.uk/bitstream/handle/10399/2170/ThemelisS_1008_sbe.pdf?sequence=1 (accessed: 24.02.2025)
2. Wilson EL. *Static & Dynamic Analysis of Structures: a Physical Approach with Em-Phasis on Earthquake Engineering*. – Computers and Structures Inc, 2004.
3. Mailyan LR, Zubritsky MA, Ushakov OYu, Sabitov LS. Calculation of High-Rise Structures Under Seismic Impact of the Control Earthquake Level by the Nonlinear Static Method on the Example of the Adyghe Wind Farm. *Construction Materials and Products*. 2020;3(1):14–20. (In Russ.) https://doi.org/10.34031/2618-7183-2020-3-1-14-20
4. Mailyan DR, Muradyan VA. Method of Calculating Eccentrically Compressed Concrete Columns. *Engineering Bulletin of the Don*. 2012; 4–2(23):182. (In Russ.) URL: http://www.ivdon.ru/ru/magazine/archive/n4p2y2012/1333 (accessed: 24.02.2025)
5. Muselemov HM, Mailyan DR, Muselemov DU. Stress-Strain State of a Three-Layer Tubular Structure under the Influence of a Uniformly Distributed Pulse Load. *Engineering Bulletin of the Don.* 2023;11(107):386–400. (In Russ.) URL: http://www.ivdon.ru/ru/magazine/archive/n11y2023/8786 (accessed: 24.02.2025)
6. Pshenichkina VA, Drozdov VV, Chauskin AY *Seismic Reliability of High-Rise Buildings*. Volgograd: Publishing House of Volgograd State Technical University; 2022. 180 p. (In Russ.)
7. Mailyan LR, Stelmakh SA, Shcherban EM. Calculation and Design of Building Structures Taking into Account the Variotropy of Structure, Sections and Differentiation of Structural Characteristics of Materials. *Scientific Journal of Construction and Architecture.* 2021;2(62):27–48. (In Russ.) https://doi.org/10.36622/VSTU.2021.62.2.002
8. Mailyan LR, Zubritsky MA, Ushakov OYu, Sabitov LS, Bambulevich MD. Seismic Resistance Estimation of Existing Turbogenerator Foundation Structures under Ductility Level Earthquake Impact by Nonlinear Static Method. *Academic Bulletin of UralNIIproekt RAASN*. 2020;4(47):79–83. (In Russ.) https://doi.org/10.25628/UNIIP.2020.47.4.013
9. Mailyan LR, Yazyev SB, Sabitov LS, Konoplev YuG, Radaykin OV Stress-Strain State of the System "Combined Tower - Reinforced Concrete Foundation - Foundation Soil" of High-Rise Buildings. *Construction Materials and Products.* 2019;2(6):29–37. (In Russ.) https://doi.org/10.34031/2618-7183-2019-2-6-29-37
10. Abakanov T, Kusainov AA, Teplykh AV, Bondarev DE. *Seismology and Seismic Resistance of Structures.* Moscow: SKAD SOFT Publishing House, ASV Publishing House; 2024. 624 p. (In Russ.) URL: https://iasv.ru/sejsmologiya-i-sejsmostojkost-sooruzhenij.html (accessed: 24.02.2025).

11. Mazhiev KhN, Bataev DK-S, Gaziev MA, Mazhiev KKh, Mazhieva AKh *Materials and Structures for the Construction and Restoration of Buildings and Structures in Seismic Areas*. Grozny: Kh. Ibragimov Complex Institute of the Russian Academy of Sciences; 2014. 652 p. (In Russ.)

12. Mazhiev KhN, Mazhiev KKh, Panasenko YuV, Mazhieva AKh, Mazhiev AKh., Mazhiev AKh. Adhering to Regulatory Requirements in Calculation of Earthquake Resistance of the Structures of Life-Saving Buildings. *Modern Trends in Construction, Urban and Territorial Planning.* 2024;3(4):17–29. (In Russ.) https://doi.org/10.23947/2949-1835-2024-3-4-17-29

13. Mazhiev KhN, Mazhiev KKh, Mazhieva AKh, Semenov SYu, Mazhiev AKh, Mazhiev AKh. Structural System and Computational Dynamic Model of a Life-Saving Multi-Storey Building with a Kinematic Seismic Isolation System. *Modern Trends in Construction, Urban and Territorial Planning.* 2024;3(3):71–82. (In Russ.) https://doi.org/10.23947/2949-1835-2024-3-3-71-82

14. *Scientific and Technical Expertise on the Topic: "Scientific and Technical Support for the Design of a Cultural Heritage Site of Regional Significance "Aurora Cinema", 1967, located at Krasnodar, Krasnaya St., 169, lit. A. Reconstruction and Adaptation for Modern Use." Volume 1. Cinema and Variety Hall (Block A1).* Moscow: Central Research Institute of Building Structures named after VA Kucherenko, JSC "Research Center "Construction"; 2024. 65 p. (In Russ.)

15. *Recommendations for Accounting for the Wave Nature of Seismic Impact and Protection against Emergencies.* Moscow, V.A. Kucherenko Central Research Institute of Structures, 2024. (In Russ.)

About the authors:

Khasan N. Mazhiev, Dr.Sci. (Eng.), Professor, Head of the Department of Building Structures of the Federal State Budgetary Educational Institution of Higher Education Grozny State Oil Technological University named after Academician M.D. Millionshchikov (100 Kh.A. Isaev pr-t, Grozny, Chechen Republic, 364051, Russian Federation), ORCID, seismofund@mail.ru

Kazbek K. Mazhiev, Cand.Sci. (Eng.), Scientific Director of the Scientific and Technical Center "Safety of Buildings and Structures under Natural and Man-Made Impacts", Associate Professor of the Building Structures Department, Federal State Budgetary Educational Institution of Higher Education "Grozny State Oil Technological University named after Academician M.D. Millionshchikov" (100 Kh.A. Isaev pr-t, Grozny, Chechen Republic, 364051, Russian Federation); Senior Researcher, Federal State Budgetary Institution of Science "Integrated Research Institute named after Kh.I. Ibragimov of the Russian Academy of Sciences" (21a V. Aliyev str. Grozny, Chechen Republic, 364051, Russian Federation), ORCID, seismofund@mail.ru

Yuri V. Panasenko, Head of the expert calculations group of the Laboratory of Automation of Research and Design of Structures, Central Research Institute of Building Structures named after V.A. Kucherenko, JSC "Research Center "Construction" (6, 2-ya Institutskaya St., Moscow, 109428, Russian Federation), ORCID, panyuriy@eurosoft.ru

Amina K. Mazhieva, Cand.Sci. (Eng.), Associate Professor of the Department of Building Structures, Federal State Budgetary Educational Institution of Higher Education "Grozny State Oil Technical University named after Academician M.D. Millionshchikov" (100 Kh.A. Isaev pr-t, Grozny, Chechen Republic, 364051, Russian Federation), ORCID, seismofund@mail.ru

Aslan K. Mazhiev, Researcher, Department of Physical, Mathematical and Technical Sciences, Center for Materials Science Problems, State Scientific Institution "Academy of Sciences of the Chechen Republic" (19a Vahi Aliyev str., Grozny, Chechen Republic, 364043, Russian Federation); Senior Lecturer, Department of Building Structures, Federal State Budgetary Educational Institution of Higher Education, Grozny State Oil Technological University named after Academician M.D. Millionshchikov" (100 Kh.A. Isaev pr-t, Grozny, Chechen Republic, 364051, Russian Federation), ORCID, seismofund@mail.ru

Adam K. Mazhiev, Researcher, Department of Physical, Mathematical and Technical Sciences, Center for Materials Science Problems, State Scientific Institution "Academy of Sciences of the Chechen Republic" (19a Vahi Aliyev str., Grozny, Chechen Republic, 364043, Russian Federation), ORCID, seismofund@mail.ru

Claimed Contributorship:

KhN Mazhiev: scientific supervision, formation of the main concept, goals, objectives of the study and its general planning, participation in the implementation of the study, analysis of its results, revision and development of conclusions, correction of the manuscript.

KKh Mazhiev: participation in the implementation of the study, analysis of the obtained results, correction of the manuscript, formulation of conclusions.

AKh Mazhieva: participation in the implementation of the research, in the development of a computational and dynamic model of the building, analysis of the results obtained, formulation of the conclusions.

YuV Panasenko: development of a computational and dynamic model of the building, calculations, implementation of the main stages of the study, processing and analysis of the obtained results, formulation of conclusions.

AKh Mazhiev: participation in calculations, implementation of the main stages of the research, processing and analysis of the results obtained, formulating conclusions, preparing illustrations, the original text and general design of the manuscript.

AKh Mazhiev: participation in calculations, implementation of the main stages of the study, processing and analysis of the obtained results, formulating conclusions.

Conflict of interest: the authors declare no conflict of interest.

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

Об авторах:

Хасан Нажоевич Мажиев, доктор технических наук, профессор, заведующий кафедрой строительных конструкций Грозненского государственного нефтяного технического университета имени академика М.Д. Миллионщикова (364051, Российская Федерация, Чеченская Республика, г. Грозный, пр-т им. Х.А. Исаева, 100), ORCID, seismofund@mail.ru

Казбек Хасанович Мажиев, кандидат технических наук, научный руководитель Научно-технического центра «Безопасность зданий и сооружений при природных и техногенных воздействиях», доцент кафедры строительных конструкций Грозненского государственного нефтяного технического университета имени академика М.Д. Миллионщикова (364051, Российская Федерация, Чеченская Республика, г. Грозный, пр-т им. Х.А. Исаева, 100); старший научный сотрудник Комплексного научно-исследовательского института им. Х.И. Ибрагимова Российской академии наук (364051, Российская Федерация, Чеченская Республика, г. Грозный, ул. В. Алиева, 21а), ORCID, seismofund@mail.ru

Юрий Вячеславович Панасенко, руководитель группы экспертных расчетов лаборатории автоматизации исследований и проектирования сооружений Центрального научно-исследовательского института строительных конструкций имени В.А. Кучеренко АО «НИЦ «Строительство» (109428, Российская Федерация, г. Москва, ул. 2-я Институтская, 6), ORCID, panyuriy@eurosoft.ru

Амина Хасановна Мажиева, кандидат технических наук, доцент кафедры строительных конструкций Грозненского государственного нефтяного технического университета имени академика М.Д. Миллионщикова (364051, Российская Федерация, Чеченская Республика, г. Грозный, пр-т им. Х.А. Исаева, 100), ORCID, seismofund@mail.ru

Аслан Хасанович Мажиев, научный сотрудник отдела физико-математических и технических наук Центра проблем материаловедения Академии наук Чеченской Республики (364043, Российская Федерация, Чеченская Республика, г. Грозный, ул. В. Алиева, 19а); старший преподаватель кафедры строительных конструкций Грозненского государственного нефтяного технического университета имени академика М.Д. Миллионщикова (364051, Российская Федерация, Чеченская Республика, г. Грозный, пр-т им. Х.А. Исаева, 100), ORCID, seismofund@mail.ru

Адам Хасанович Мажиев, научный сотрудник отдела физико-математических и технических наук Центра проблем материаловедения Академии наук Чеченской Республики (364043, Российская Федерация, Чеченская Республика, г. Грозный, ул. В. Алиева, 19а), ORCID, seismofund@mail.ru

Заявленный вклад авторов:

Х.Н. Мажиев: научное руководство, формирование основной концепции, цели, задач исследования и его общее планирование, участие в реализации исследования, анализ его результатов, доработка и развитие выводов, корректировка рукописи.

К.Х. Мажиев: участие в реализации исследования, анализ полученных результатов, корректировка рукописи, формулирование выводов.

А.Х. Мажиева: участие в реализации исследования, в разработке расчетно-динамической модели здания, анализ полученных результатов, формулирование выводов.

Ю.В. Панасенко. разработка расчетно-динамической модели здания, проведение расчетов, реализация основных этапов исследования, обработка и анализ полученных результатов, формулирование выводов.

А.Х. Мажиев: участие в проведении расчетов, реализация основных этапов исследования, обработка и анализ полученных результатов, формулирование выводов, подготовка иллюстраций, первоначального текста и общее оформление рукописи.

А.Х. Мажиев: участие в проведении расчетов, реализация основных этапов исследования, обработка и анализ полученных результатов, формулирование выводов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 02.03.2025
Reviewed / Поступила после рецензирования 15.03.2025
Accepted / Принята к публикации 09.04.2025

FOUNDATIONS AND UNDERGROUND STRUCTURES

ОСНОВАНИЯ И ФУНДАМЕНТЫ, ПОДЗЕМНЫЕ СООРУЖЕНИЯ

Check for updates

Original Empirical Research

UDC 624.15:699.841
https://doi.org/10.23947/2949-1835-2025-4-2-38-48

EDN: VWWGDC

Performance-Based Plastic Design of a Reinforced Concrete Frame for Seismic Loads Considering the Soil-Pile-Structure Interaction

Mohamed Abdelhamid Elsayed Mohamed, **Albert Yu. Prokopov** ✉
Don State Technical University, Rostov on Don, Russian Federation
✉ prokopov72@rambler.ru

Abstract
Introduction. The authors make use of Performance-Based Plastic Design (PBPD) method that is commonly employed overseas for calculations and design of building structures in seismic hot spots. A pre-selected target drift and yield mechanisms is used as the key performance objectives. In this research, reinforced concrete special moment frames (RC SMF) were analyzed for high-rise concrete structures perceiving seismic loads.
Materials and Methods. Two designs were considered in the analysis, one according to ACI-318/ASCE-07, and the other according to PBPD. RC SMF was also combined with pile caps and piles foundation system to provide a soil-pile-structure interaction (SPSI) model. Nonlinear lateral load-transfer from the foundation to the soil is modeled using p-y curves for soft clay soil that was considered in this study.
Results. Numerical results obtained using soil-pile- structure interaction model conditions were compared to those corresponding to fixed-base support conditions, such as fundamental time period, structural capacity, story displacement and story drift. Frames designed using PBPD were less affected by SPSI, in spite of having greater values in general than frames designed following the standards (codes).
Discussion and Conclusions. The PBPD method as a direct design method where the drift control and the selection of yield mechanism are initially assumed in the design work, proved that it is an effective method to reach a better performance for reinforced concrete moment resisting frames with fixed base support.

Keywords: Performance-Based Plastic Design (PBPD); Reinforced Concrete Special Moment Frames (RC SMF); Soil-Pile-Structure Interaction (SPSI); P-Y Curve; Pushover Analysis

For citation. Mohamed AEM, Prokopov AYu. Performance-Based Plastic Design of a Reinforced Concrete Frame for Seismic Loads Considering the Soil-Pile-Structure Interaction. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):38–48. https://doi.org/10.23947/2949-1835-2025-4-2-38-48

Оригинальное эмпирическое исследование

Расчет железобетонного каркаса на сейсмические нагрузки с учетом взаимодействия системы «грунт-свая-конструкция» в нелинейной постановке

Мохамед Абдельхамид Эльсаед Мохамед, **А.Ю. Прокопов** ✉
Донской государственный технический университет, Ростов на Дону, Российская Федерация
✉ prokopov72@rambler.ru

Аннотация
Введение. В статье применен «метод пластического проектирования на основе эксплуатационных характеристик» (PBPD), который получил широкое распространение в зарубежной практике расчета и проектирования строительных конструкций в сейсмически опасных регионах. В качестве допустимых параметров используются предварительно выбранные значения смещений конструкций и текучести материалов. В данном исследовании

были проанализированы специальные железобетонные «моментные» рамы (RC SMF) для высотных зданий, воспринимающих сейсмические нагрузки.

Материалы и методы. Для анализа рассматривалось проектирование двух вариантов конструкций: первый — в соответствии с международными стандартами ACI-318/ASCE-07, второй – в соответствии с методом PBPD. Каркас из железобетонных рам RC SMF был объединен с ростверком и системой свайных фундаментов для создания модели взаимодействия «грунт-свая-конструкция» (SPSI-модель). Нелинейная передача боковой нагрузки от фундамента к грунту моделируется с помощью кривых P-Y (нагрузка – перемещение) для мягкопластичного глинистого грунта, рассматриваемого в данном исследовании.

Результаты исследования. Численные результаты, полученные с использованием условий модели взаимодействия грунта со сваями, сравнивались с результатами, соответствующими условиям неподвижного основания, по таким факторам, как фундаментальный период, прочность конструкции, горизонтальные и вертикальные перемещения узлов на разных этажах. Рамы, спроектированные с использованием метода PBPD, были менее подвержены влиянию взаимодействия системы «грунт-свая-конструкция» SPSI, хотя в целом имели более высокие значения армирования, чем рамы, спроектированные по действующим нормам (кодам).

Обсуждение и заключение. Метод PBPD как метод прямого проектирования конструкций, при котором в расчетной схеме изначально предполагается контроль смещения конструкций, доказал, что он обеспечивает наиболее корректные параметры железобетонных рам, воспринимающих моменты от проектных нагрузок при задании неподвижной опоры здания.

Ключевые слова: пластическое проектирование на основе эксплуатационных характеристик (PBPD); железобетонные специальные моментные рамы (RC SMF); взаимодействие «грунт-свая-конструкция» (SPSI); кривая P-Y; анализ продавливания

Для цитирования. Мохамед Абдельхамид Эльсаед Мохамед, Прокопов А.Ю. Расчет железобетонного каркаса на сейсмические нагрузки с учетом взаимодействия системы «грунт-свая-конструкция» в нелинейной постановке. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):38–48. https://doi.org/10.23947/2949-1835-2025-4-2-38-48

Introduction. Performance-Based Plastic Design (PBPD) method was derived from the Performance based Seismic design PBSD method. Performance-based Plastic design method starting from the pre-defined performance objectives, in which the intended yield mechanism is achieved through performing plastic design. Plastic design controls drift and yielding of frame members from the beginning to minimize the lengthy iterations to reach the final design [1–7].

Soil-structure interaction (SSI) analysis simulates the combined response of the three connected systems: structure, foundation, and soil supporting the foundation. The ratio, h / (Vs T), is the structure-to-soil stiffness ratio, and can be used to determine when the soil-structure-interaction effect is significant so that h is approximately two-thirds of the building height, this height represents the center of mass height for the first mode shape, Vs is shear wave velocity of the soil, and T is the fundamental time period of the structure with fixed-base supports [8]. Soil-structure interaction can lengthen the structure time period significantly when structure-to-soil stiffness ratio exceeds 0.1, the change in time period will directly change the design base shear compared with fixed-base analysis [8 and 9]. In some cases when the increase in time period due to soil-structure interaction causes an increase in spectral acceleration, the SSI effect must be evaluated [10].

The numerical model that simulates the soil resistance to lateral displacement as predefined nonlinear springs is called *p–y* curve, where p is the soil pressure per unit length of the pile and y is the pile lateral deflection. The soil is represented by a series of nonlinear *p–y* curves that vary with depth and soil type. The *p–y* curves are used to relate pile deflections to the nonlinear soil reactions [11-13].

The Matlock theory [11] is used for laterally loaded piles in soft clays to determine *p–y* curves as illustrated in Equations 1 and 2. Fig. 1 presents the schematic shape of *p–y* curve for soft clay as per Matlock model. Nonlinear lateral load-transfer from the foundation to the soil is modeled using *p–y* curves generated by the PyPile v.0.6.3 software program for soft clay soil.

$$p = 0{,}5p_u\left(\frac{Y}{Y_{50}}\right)^{\frac{1}{3}}, \frac{Y}{Y_{50}} \le 8 \quad (1)$$

$$p = p_u, \frac{Y}{Y_{50}} > 8 \quad (2)$$

$$Y_{50} = 2{,}5\varepsilon_{50}D \quad . \quad (3)$$

where, ε_{50} is the strain which occurs at one-half the maximum stress on laboratory unconsolidated undrained compression tests of undisturbed soil samples, and *D* is the pile diameter.

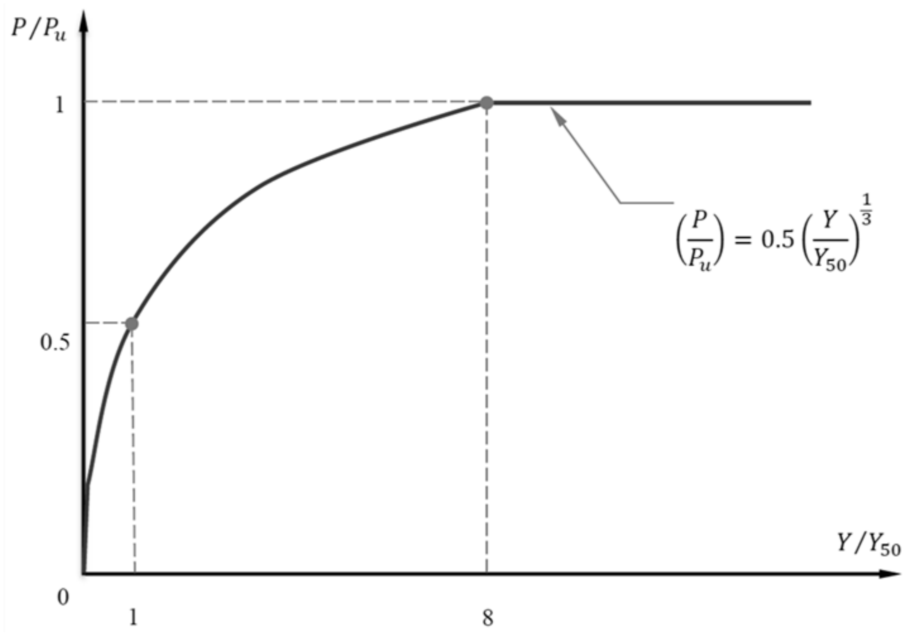


Fig. 1. Soft clay (Matlock) model

Materials and Methods

Statement of the Problem. Three baseline RC structures (8, 12 and 20-floor internal RC special moment frame structure) as used in the FEMA P695 [14], was selected for this study. The frames are used to support both vertical and lateral loads. These (code-based design) structures were redesigned by means of the PBPD approach as shown in Table 1 [1]. The baseline structure and the PBPD structure were subjected to extensive inelastic pushover analysis, then tested considering soil-pile-structure interaction (SPSI).

Input Data

The building is designed to sustain the following loading data:

– Design floor dead load = 8.38 kN/m^2 (175 psf).

– Design floor live load = 2.40 kN/m^2 (50 psf).

Material Properties

– Concrete cylinder compressive strength *fc*' = 34.5–41.4 MPa (5.0–6.0 ksi)

– Reinforcement rebar yield strength *fy* = 413.7 MPa (60.0 ksi)

Soil Properties

Soft clay soil is used for soil-pile-structure interaction modeling. Properties for this type of soil are as follows [15]:

– Dry Density = 17.50 kN/m^3

– Poisson's Ratio = 0.4

– Young's Modulus = 8 N/mm^2

Table 1

Building configuration and design parameters

Design Parameters	8–floor	12–floor	20–floor
ID Number	1012	1014	1021
Number of Floors	8	12	20
First Floor Height, m (ft)	4.572 (15)		
Upper Floor Height, m (ft)	3.962 (13)		
Bay Size, m (ft)	6.096 (20)		
Total Height, m (ft)	32.309 (106)	48.158 (158)	79.858 (262)
Code Compliant Base Shear, kN (kip)	418.1 (94)	547.1 (123)	907.4 (204)
PBPD Compliant Base Shear, kN (kip)	632.5 (142.2)	746 (167.7)	1567.1 (352.3)

Model Description. SAP2000 v20 software analysis package was used in this study to perform pushover analysis. Twelve models were produced as described in Table 2. 2D-models were created for each case and P-Delta effect was considered in all of them (Fig. 2). The foundation soil-pile system is modeled by replacing the support by thick shell elements representing pile cap supported on piles as indicated, and joined to link elements that simulates the soil resistance using p-y curves, in addition to a linear spring at the bottom end of the pile to provide a vertical support with elastic stiffness equals pile capacity divided by 0.01 m as an accepted allowable settlement. For SPSI models, the piles were 20 and 25 m long for the 8- and (12-, 20-) floor buildings, respectively, and having a diameter of 1.0 m and 1.2 m for the (8-, 12-) and 20-floor buildings, respectively.

Table 2

Analysis models produced

Model Description	Design Following					
	The Code			PBPD		
	8	12	20	8	12	20
Without SPSI	√	√	√	√	√	√
With SPSI	√	√	√	√	√	√

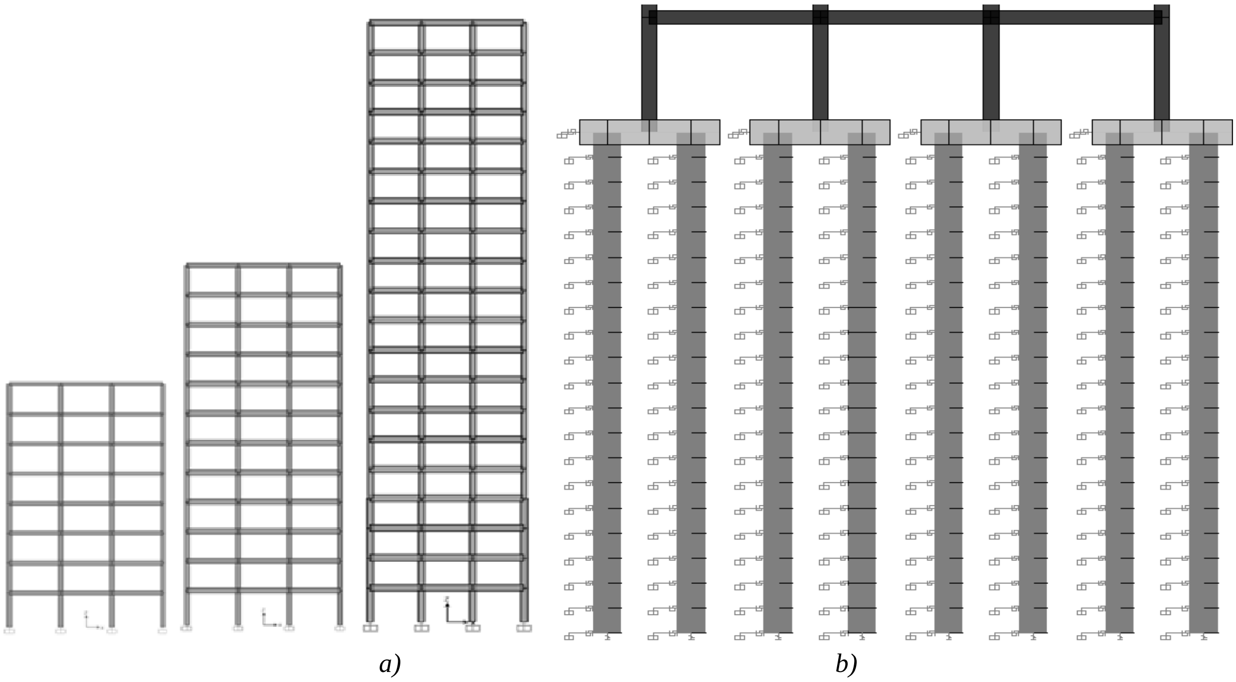


Fig. 2. 2D-models *a* — SAP2000 2D-Model – Without SPSI;
b — SAP2000 2D-Model – With SPSI

Results

Fundamental Time Period. Fundamental time period values for fixed-base structures and those with soil-pile-foundation system are listed in Table 3. Deep foundation is expected to provide a rigid support for the structure in the vertical direction, but the lateral stiffness of the system (soil-pile-foundation) is affected by the soil. The time period of frames used to study SPSI increased depending on structural flexibility (reflected by the building height). The frames designed using PBPD showed a smaller increase in time period than those designed following the code.

Table 3

Analysis models produced

Model Description	Design Following					
	Code			PBPD		
	8	12	20	8	12	20
Without SPSI	1.79	2.29	2.91	1.82	2.03	2.41
With SPSI	2.27	2.78	3.14	2.20	2.37	2.64
Percent increase	27 %	21 %	8 %	21 %	17 %	10 %

Drift and Displacement. The outputs of pushover analysis (P-Delta Curve) were used to compare the changes in the inter-floor drift and roof displacement. The maximum inter-story drift at the structural capacity, and roof displacement at the maximum base shear (reference to the base) were collected, summarized and presented in Table 4 and Fig. 3 and 4. Both inter-floor drift and roof displacement were affected by the soil flexibility. Frames designed using PBPD were less affected by SPSI, in spite of having greater values in general than those designed following the code.

Table 4

Maximum inter-floor drift ratios and roof displacement at the maximum base shear

Model Description	Design Following					
	The Code			PBPD		
	8	12	20	8	12	20
Max. Inter-Floor Drift						
Without SPSI	0.89%	0.86%	1.26%	1.87%	1.80%	1.67%
With SPSI	0.82%	0.92%	1.30%	1.88%	1.80%	1.70%
Max. roof displacement (m)						
Without SPSI	0.182	0.207	0.433	0.467	0.528	0.730
With SPSI	0.174	0.226	0.455	0.476	0.535	0.756

Capacity and Base Shear. As per FEMA 356 [10], structural performance level “Life Safety (LS)” means the post-earthquake damage state in which significant damage to the structure has occurred, but some margin against either partial or total structural collapse remains. While structural performance level “Collapse Prevention (CP)” means the post- earthquake damage state in which the building is on the verge of partial or total collapse. However, all significant components of the gravity-load-resisting system must continue to carry their gravity load demands. Structural performance levels for allowable drift will not exceed 2% and 4% for LS and CP, respectively. In this study the allowable drift for CP will be limited to 3% only.

The P-Delta curves results from pushover analysis for all the 12 models, modified to be Base shear ratio versus Lateral drift ratio, are presented in Fig. 5 and 6. The structural capacity at a 2% drift ratio, a 3% drift ratio and the maximum capacity base shear are presented in Table 5 and 6.

In general, (for fixed-base frames) the frame capacity for frames designed using PBPD is less than that for those designed following the code, and exceeds the targeted design base shear. When introducing SSI into the equation, the capacity of all the frames depends on the soil flexibility.

Table 5

Structural capacity at a 2% drift ratio and at a 3% drift ratio of the structures

Model Description	Design Following					
	The Code			PBPD		
	8	12	20	8	12	20
Structural capacity at a 2% drift ratio						
Without SPSI	NR	NR	NR	685	812	1033
With SPSI	NR	NR	NR	685	812	1073
Structural capacity at a 3% drift ratio						
Without SPSI	NR	NR	NR	577	NR	NR
With SPSI	NR	NR	NR	577	NR	NR
NR = Not Reached, Structure did not maintain the capacity to this drift ratio						

Table 6

Maximum capacity base shear of the structures

Model Description	Design Following					
	The Code			PBPD		
	8	12	20	8	12	20
Without SPSI	876	982	1520	714	902	1770
With SPSI	870	973	1508	707	891	1763

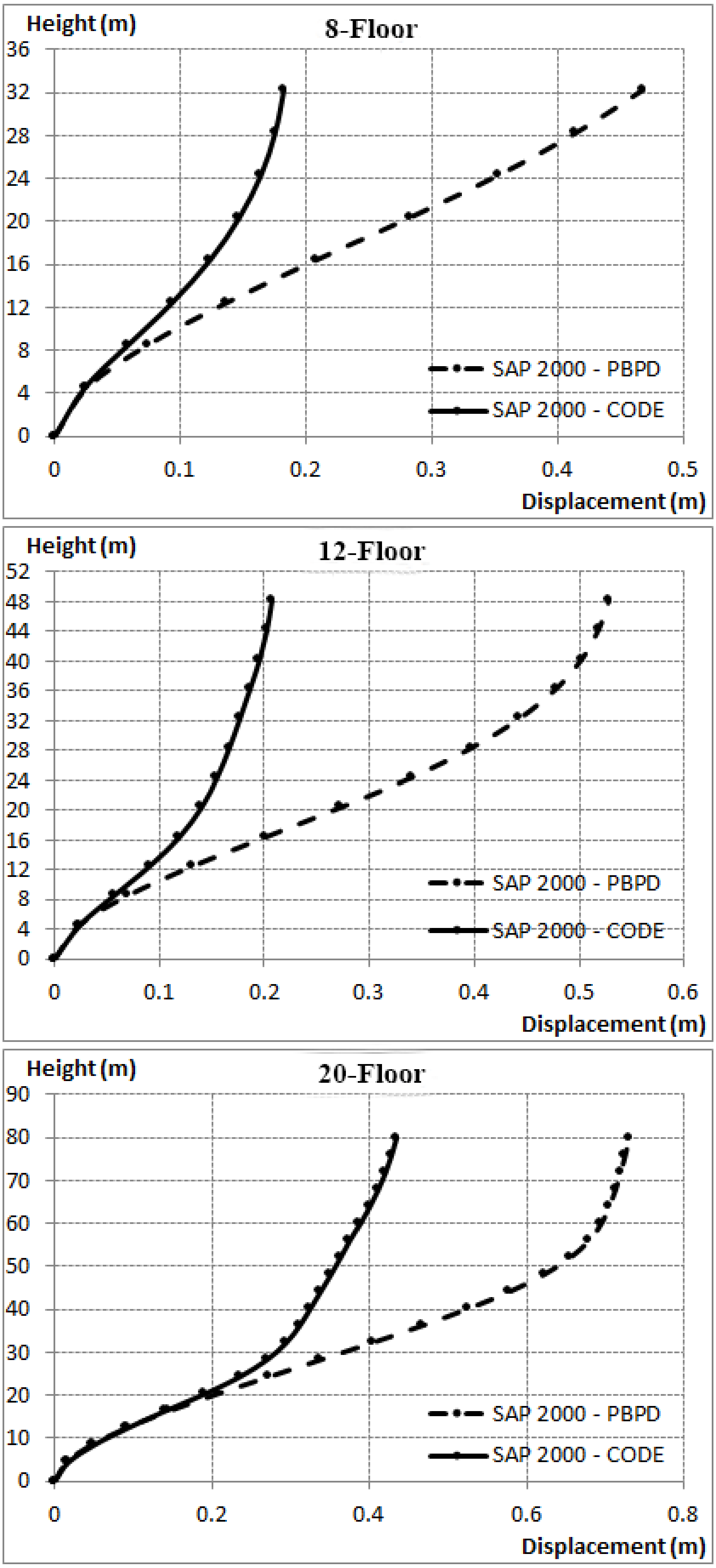


Fig. 3. Floor Displacement – Without SPSI – Fixed-base support, for 8-, 12- and 20- floor

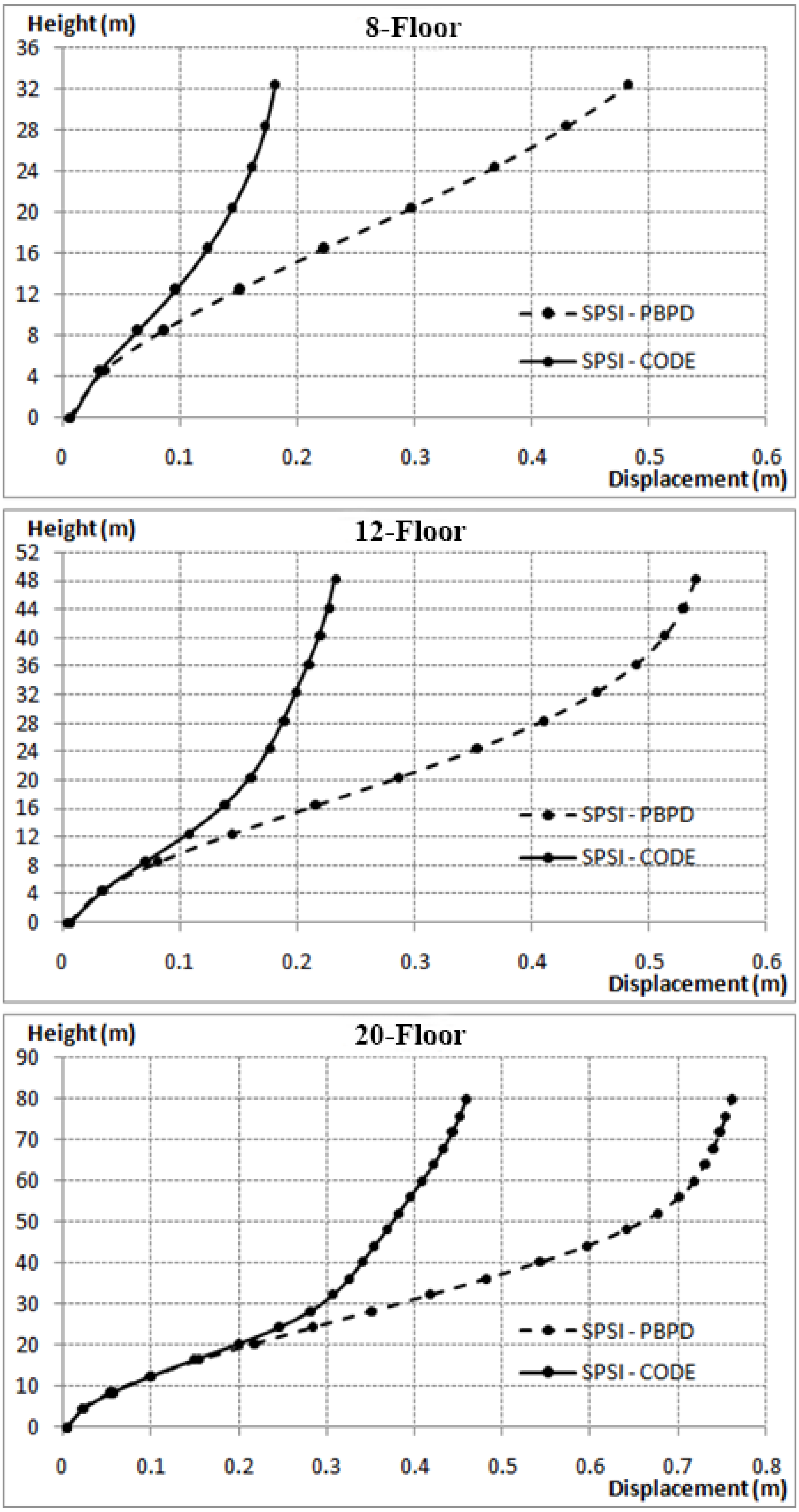


Fig. 4. Floor Displacement – With SPSI, for 8, 12 and 20 floor

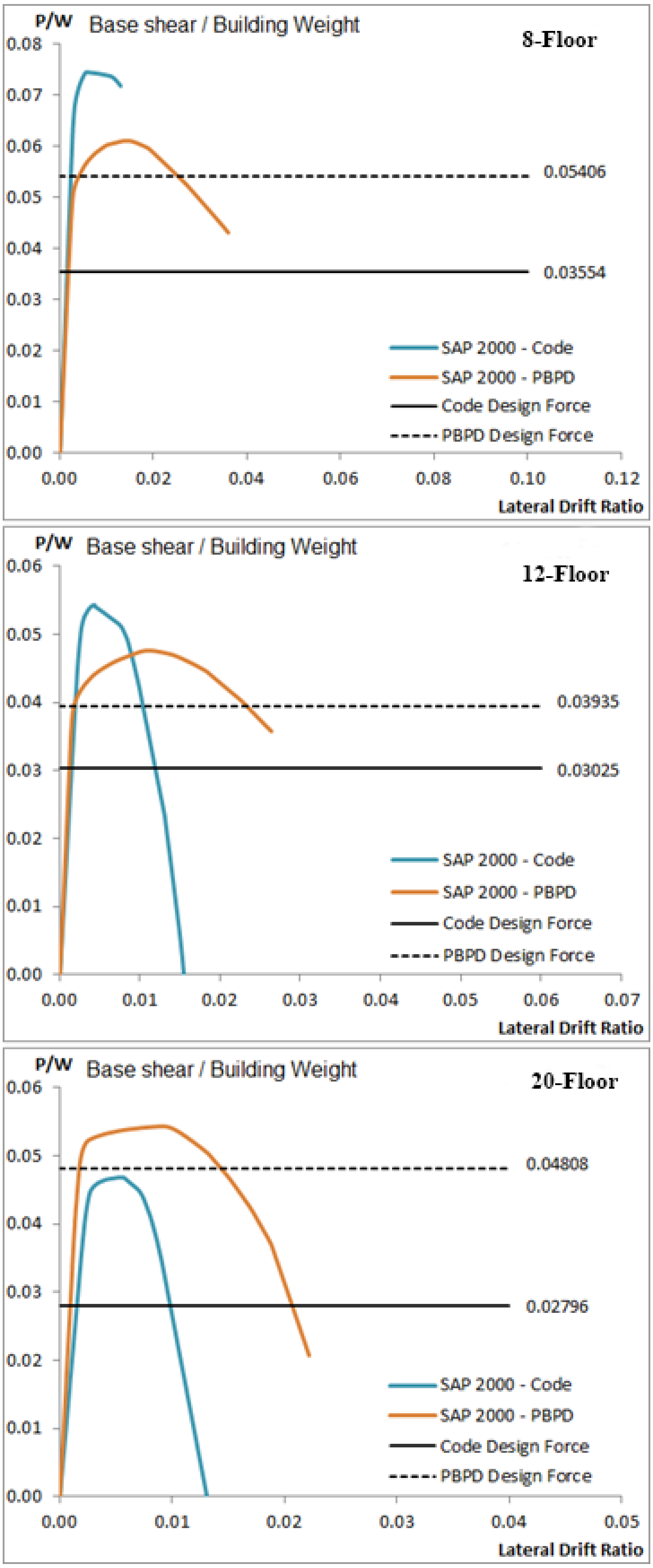


Fig. 5. Base shear ratio versus lateral drift ratio for a fixed base, for 8-, 12- and 20- floor

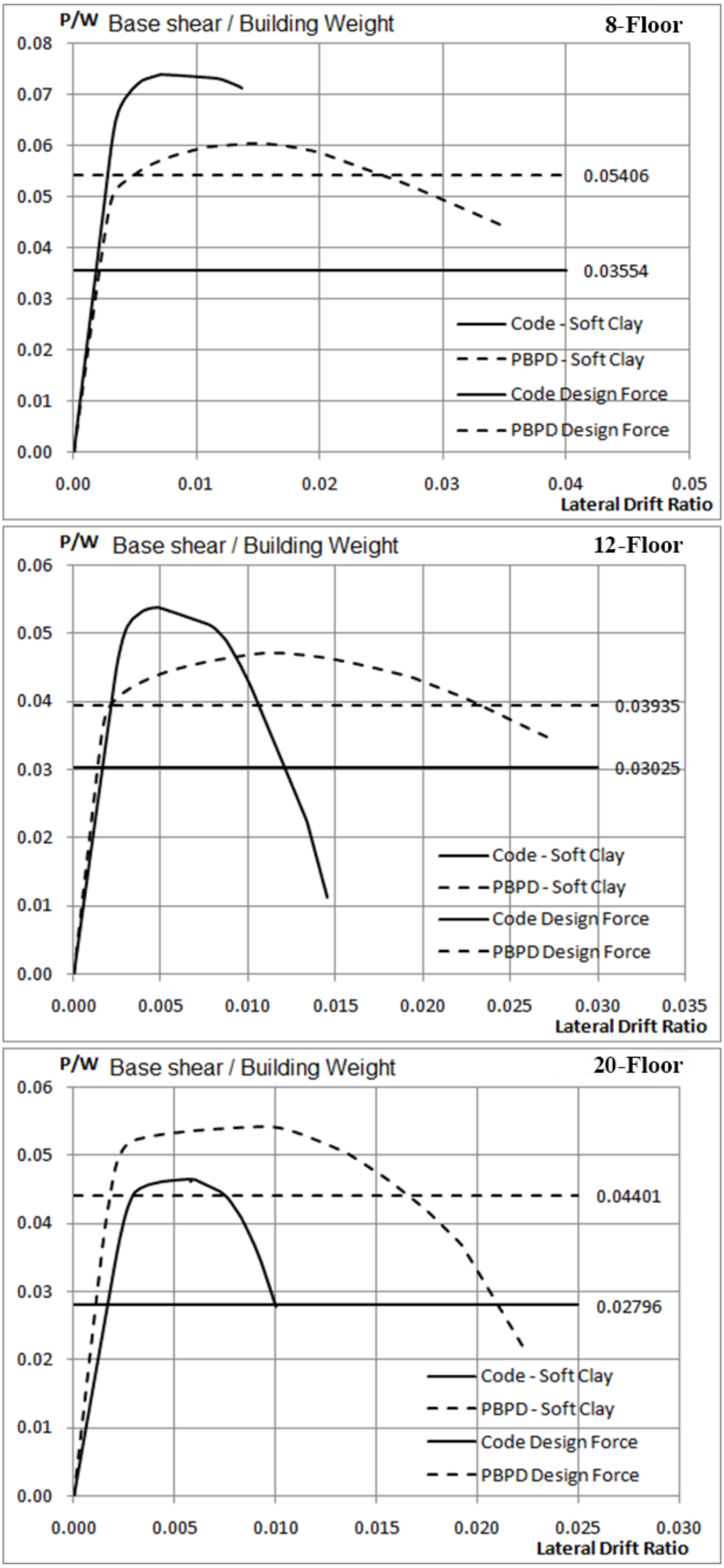


Fig. 6. Base shear ratio versus lateral drift ratio considering SPSI

Discussion and Conclusion. The PBPD method as a direct design method where the drift control and the selection of yield mechanism are initially assumed in the design work proved that it is an effective method to reach a better performance for reinforced concrete moment resisting frames with a fixed-base support. It does not need lengthy iterations to achieve a suitable final design. On the other hand, considering the soil-structure interaction introduces other variables to the equation. SPSI can change the behavior of the fixed-base structure. This paper presents an assessment of the original code design and the PBPD methods to design RC SMF systems considering the soil-pile-structure interaction. The main conclusions are as follows.

1. *The Natural Time Period*
   - The natural time period varies significantly from a fixed-base to a flexible base structure (considering SPSI).
   - Considering SPSI leads to an increase in time period.
   - Time period due to SPSI increases as does the building height; while period lengthening decreases as the building height increases.
2. *Drift and Displacement*
   - The use of the PBPD method increases an inter-floor drift ratio.
   - Considering SPSI increases an inter-floor drift and roof displacement for both design methods.
3. *Capacity and Base shear*
   - PBPD can produce structures that meet preselected performance objectives in terms of the yield mechanism and target drift.
   - Frame capacity designed using PBPD is generally less than that of code elastic design.
   - Considering SPSI reduces the capacity of frames designed following the code elastic design and PBPD.

Frames with a fixed base and designed following the code elastic design failed to reach the 2% Life Safety drift limit and the 3% Collapse Prevention drift limit, while the one designed following PBPD method reached a capacity exceeding the design base shear, except in the case of the 20-floor structure. The 12-floor structure almost reached a 3% drift limit reaching 2.8%.

At a 2% Life Safety drift limit, frames designed using PBPD maintained its capacity, with minor loss in strength. When considering SPSI minor losses in strength occurs, except for the 20-floor structure where major strength loss happens.

For models following the code elastic design method, considering SPSI causes a significant loss in strength, ductility and a 3% drift limit is not reached. On the other hand, PBPD improves the ductility of the frames but did not reach a 3% drift limit at the ultimate drift, except in the case of the 8-floor structure.

References

1. Liao WC, Goel SC Performance-Based Seismic Design of RC SMF Using Target Drift and Yield Mechanism as Performance Criteria. *Advances in Structural Engineering*, 2014;17(4):529–542. https://doi.org/10.1260/1369-4332.17.4.529

2. Goel SC, Liao WC, Reza Bayat M, Chao SH Performance-Based Plastic Design (PBPD) Method for Earthquake-Resistant Structures: an Overview. *The Structural Design of Tall and Special Buildings*, 2010;19(1–2):115–137. https://doi.org/10.1002/tal.547

3. Banihashemi MR, Mirzagoltabar AR, Tavakoli HR Development of the Performance Based Plastic Design for Steel Moment Resistant Frame. *International Journal of Steel Structures*, 2015;15(1):51–62. https://doi.org/10.1007/s13296-015-3004-6

4. Banihashemi MR, Mirzagoltabar AR, Tavakoli HR Performance-Based P lastic D esign M ethod for S teel C oncentric B raced Frames. *International Journal of Advanced Structural Engineering (IJASE)*, 2015;7(3):281–293. https://doi.org/10.1007/s40091-015-0099-0

5. Goel SC, Chao SH, Leelataviwat S, Lee Soon-Sik Performance-Based Plastic Design (PBPD) Method for Earthquake-Resistant Structures. *The 14th World Conference on Earthquake Engineering*. (2008, October 12–17). Beijing, China. https://www.iitk.ac.in/nicee/wcee/article/14_05-01-0036.PDF (accessed: 23.03.2024)

6. Lee SS, Goel SC, Chao SH Performance-Based Seismic Design of Steel Moment Frames Using Target Drift and Yield Mechanism. *13th World Conference on Earthquake Engineering*. (2004, August) Vancouver, BC: Canada. https://www.researchgate.net/publication/265099359_Performance-based_design_of_steel_moment_frames_using_target_drift_and_yield_mechanism (accessed: 23.03.2024)

7. Zameeruddin M, Sangle KK Review on Recent Developments in the Performance-Based Seismic Design of Reinforced Concrete Structures. Elsevier. *Structures*, 2016;6:119–133. https://doi.org/10.1016/j.istruc.2016.03.001

8. Soil-Structure Interaction for Bbuilding S tructures. US Department of Commerce. NISTGCR 12-917-21, 2012. https://www.nist.gov/publications/soil-structure-interaction-building-structures (accessed: 22.03.2024)

9. Federal Emergency Management Agency. Improvement of Nonlinear Static Seismic Analysis Procedures. FEMA 440, Applied Technology Council (ATC-55 Project). 2005.

10. Council BSS Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Report FEMA-356, Washington, DC. 2000.

11. Matlock H. Correlation for Design of Laterally Loaded Piles in Soft Clay. *Offshore Technology in Civil Engineering's Hall of Fame Papers from the Early Years*, 1970:77–94. https://doi.org/10.4043/1204-ms

12. Boulanger RW, Curras CJ, Kutter BL, Wilson DW, Abghari A. Seismic Soil-Pile-Structure Interaction Experiments and Analyses. *Journal of Geotechnical and Geoenvironmental Engineering*, 1999;125(9):750–759. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:9(750)

13. Naggar MHE, Bentley KJ. Dynamic Analysis for Laterally Loaded Piles and Dynamic *p-y* Curves. *Canadian Geotechnical Journal*, 2000;37(6):1166–1183. https://doi.org/10.1139/t00-058

14. Applied Technology Council. Quantification of Building Seismic Performance Factors. US Department of Homeland Security, *FEMA P-695*. 2009. https://nehrpsearch.nist.gov/static/files/FEMA/fema_p695.pdf (accessed: 22.03.2024)

15. Budhu M. *Soil Mechanics and Foundations*. John Wiley & Sons. 2008

About the Authors:

Mohamed Abdelhamid Elsayed Mohamed, Master's student of the Department of Engineering Geology, Foundations and Foundations, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), ORCID, Abdelhameed1443@gmail.com

Albert Yu. Prokopov, Dr.Sci. (Eng), Professor, Head of the Engineering Geology, Footings and Foundations Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, Russian Federation, 344003), ResearcherID, ScopusID, ORCID, prokopov72@rambler.ru

Claimed contributorship:

Mohamed Abdelhamid Elsayed Mohamed: development of the idea, aims and objectives of the study, calculations, analysis and drawing conclusions, manuscript preparation, revision of the manuscript.

Prokopov AYu: scientific guidance, formation of the basic concept, revision of the manuscript; formulation of the conclusions and recommendations.

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

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

Об авторах:

Мохамед Абдельхамид Эльсаед Мохамед, магистрант кафедры инженерной геологии, оснований и фундаментов Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ORCID, Abdelhameed1443@gmail.com

Альберт Юрьевич Прокопов, заведующий кафедрой инженерной геологии, оснований и фундаментов Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), доктор технических наук, профессор, ResearcherID, ScopusID, ORCID, prokopov72@rambler.ru

Заявленный вклад авторов:

Мохамед Абдельхамид Эльсаед Мохамед: формирование основной концепции, цели и задачи исследования, расчеты на математических моделях, формирование и оформление библиографического списка.

Прокопов А.Ю.: научное руководство, анализ результатов исследований, доработка текста, формулировка выводов и рекомендаций.

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

Все авторы прочитали и одобрили окончательный вариант рукописи

Поступила в редакцию / Received 05.04.2024
Поступила после рецензирования / Revised 15.05.2024
Принята к публикации / Accepted 30.05.2024

BUILDING MATERIALS AND PRODUCTS
СТРОИТЕЛЬНЫЕ МАТЕРИАЛЫ И ИЗДЕЛИЯ

Check for updates

UDC 691.321.1
https://doi.org/10.23947/2949-1835-2025-4-2-49-56

Original Empirical Research

EDN: EHEJVC

Optimization of precast concrete production technology

Elena A. Shlyakhova ✉, **Inna O. Egorochkina**
Don State Technical University, Rostov-on-Don, Russian Federation
✉ shlyahovae@list.ru

Abstract

Introduction. The article deals with the problems of increasing the efficiency of precast concrete production technology in order to solve the issue of ensuring the required indicators of construction and technical properties of products at existing enterprises of the construction industry with no additional investment costs for their reconstruction and technical re-equipment. The aim of the work of increasing the efficiency of the production of precast reinforced concrete products is to optimize the parameters of the processes of preparing the concrete mixture as well as heat and humidity treatment of manufactured products by means of developing a two-stage method of preparing the concrete mixture and introducing a step-by-step mode into heat and humidity treatment.

Materials and Methods. The article provides a brief description of the substantive aspects of optimizing the parameters of technological operations for the preparation of concrete mixtures as well as heat and moisture treatment of precast reinforced concrete products using the example of the production of PB-type bar bridges. The manufacturing of precast reinforced concrete products using local aggregates with a high content of dusty clay particles, which determines an increase in cement consumption, is accepted as the basic object of the research.

Research Results. The proposed technology for optimizing the production modes of precast reinforced concrete makes it possible to reduce the consumption of cement and superplasticizer additives at the existing enterprises of the construction industry with no additional material and investment costs for reconstruction and technical re-equipment while using local aggregates with a high content of dusty clay particles.

Discussion and Conclusion. The application of the set of measures being developed improves the conditions for defect–free structuring of concrete and makes it possible to reduce the consumption of the most costly components of the concrete mixture, i.e., cement and the chemical additive superplasticizer. Optimization of the precast concrete production technology ensures the directed structuring of concrete and the achievement of standardized product quality indicators. In each specific case of optimizing technological solutions at each specific enterprise, it is a prerequisite to adjust the prescription and technological solutions put forward in the study. An additional effect of the implementation of the technological techniques developed in the study will be an increase in the indicators of the ecological state of the environment and a reduction in the cost of enriching local aggregates.

Keywords: precast concrete technology, preparation of concrete mix, heat and moisture treatment, optimization, quality improvement

Acknowledgements. The authors appreciate the reviewers, whose critical assessment of the submitted materials and suggestions helped to significantly improve the quality of this article.

For citation. Shlyakhova EA, Egorochkina IO Optimization of Precast Concrete Production Technology. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):49–56. https://doi.org/10.23947/2949-1835-2025-4-2-49-56

Оригинальное эмпирическое исследование

Оптимизация технологии производства сборного железобетона

Е.А. Шляхова ✉, **И.О. Егорочкина**
Донской государственный технический университет, Ростов-на-Дону, Российская Федерация
✉ shlyahovae@list.ru

Аннотация
Введение. Статья посвящена проблемам повышения эффективности технологии производства сборного железобетона для решения задачи обеспечения требуемых показателей строительно-технических свойств продукции на действующих предприятиях строительной индустрии без дополнительных инвестиционных затрат на их реконструкцию и техническое перевооружение. Целью работы по повышению эффективности производства сборных железобетонных изделий является оптимизация параметров процессов приготовления бетонной смеси и тепловлажностной обработки изготавливаемой продукции за счет разработки двухстадийного способа приготовления бетонной смеси и внедрения в процесс тепловлажностной обработки ступенчатого режима.
Материалы и методы. В статье кратко излагаются содержательные аспекты оптимизации параметров технологических операций по приготовлению бетонной смеси и тепловлажностной обработки сборных железобетонных изделий на примере производства брусковых перемычек типа ПБ. В качестве базового объекта исследований принято производство сборных железобетонных изделий с использованием местных заполнителей с повышенным содержанием пылевато-глинистых частиц, предопределяющим увеличение расхода цемента.
Результаты исследования. Предложенная технология оптимизации режимов производства сборного железобетона позволяет на действующих предприятиях стройиндустрии без дополнительных материальных и инвестиционных затрат на реконструкцию и техническое перевооружение снизить расход цемента и добавки суперпластификатора при использовании местных заполнителей с повышенным содержанием пылевато-глинистых частиц.
Обсуждение и заключение. Применение комплекса разрабатываемых мероприятий улучшает условия бездефектного структурообразования бетона и обеспечивает возможность снижения расхода наиболее дорогостоящих компонентов бетонной смеси — цемента и химической добавки суперпластификатора. Оптимизация технологии производства сборного железобетона обеспечивает направленное структурообразование бетона и достижение на этой основе нормируемых показателей качества продукции. В каждом конкретном случае оптимизации технологических решений на каждом конкретном предприятии обязательным условием является корректировка предложенных в работе рецептурно-технологических решений. Дополнительным эффектом от внедрения разработанных в настоящих исследованиях технологических приемов будет повышение показателей экологического состояния окружающей среды и снижение затрат на обогащение местных заполнителей.

Ключевые слова: технология сборного железобетона, приготовление бетонной смеси, тепловлажностная обработка, оптимизация, повышение качества

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

Для цитирования. Шляхова Е.А., Егорочкина И.О. Оптимизация технологии производства сборного железобетона. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):49–56. https://doi.org/10.23947/2949-1835-2025-4-2-49-56

Introduction. Reinforced concrete, both prefabricated and monolithic one, is presently the main building material and will remain so in the foreseeable future [1, 2]. The urgency of the problem of increasing the efficiency of precast reinforced concrete production technology at construction industry enterprises is due to the fact that its use enable one to dramatically reduce the time required for the construction, installation and commissioning of building facilities. At the same time, it should be noted that a mandatory condition for manufacturing of reinforced concrete structures is ensuring the proper quality of construction products.

Accelerated strength gain in factory conditions is due to different types of heat treatment of manufactured reinforced concrete products and structures. However, accelerated structuring of concrete of precast products and structures under heat and moisture treatment typically causes a decrease in product quality and durability of buildings and structures being built [3]. It is possible to reduce the negative effects of accelerated concrete hardening due to heat and moisture treatment by gradually increasing the temperature in steaming chambers [4]. This technique enables one to maintain the integrity of the concrete structure and to ensure the normalized quality of reinforced concrete. The negative effects of heat and moisture treatment are particularly intense when local aggregates with a high content of dusty and clay particles (DCPs) are used [5–7].

The above disadvantages of aggregates can be addressed by washing and enriching [8]. However, this not only increases the cost of aggregates, but also requires solving the issue of disposal of flushing water and pulverized waste, as well as allocating additional areas for storing washed aggregates.

As a result of countless studies, highly effective methods of activating aggregates using special equipment have been developed [9–11]. However, high costs for reconstruction and technical re-equipment of the existing construction industry enterprises prevent them from being widely used at the industrial level.

The disadvantages of the local raw material base of aggregates are commonly mitigated by increased consumption of cement, which is the most costly and rather scarce component of the concrete mix [12, 13].

The aim of these studies was to develop methods to increase the efficiency of precast concrete technology at the existing construction industry enterprises without their reconstruction and technical re-equipment, as well as with no excessive cement consumption.

The research was conducted at the operating enterprise of Rostov-on-Don, LLC TD KSM 10, using the example of the production of reinforced concrete bar lintels of the PB type, belonging to the category of prefabricated products of mass use in residential, civil and industrial construction.

Based on the analysis of some previous studies [12–14], the following tasks were identified for achieving this goal:

– development and optimization of technological parameters of two-stage concrete mix preparation;
– development of a stepwise mode of heat and moisture treatment of products;
– assessment of the ecological and economic effectiveness of the studies;
– identification of a promising field of application of the results.

Materials and Methods. The production of precast reinforced concrete lintels of the PB type was employed as the basic option. For products of this type, the concrete compressive strength class B15 was adopted, which, with a standard coefficient of variation of 13%, is 19.2 MPa. The strength of concrete following the heat and moisture treatment is normalized depending on the time of the year:

– in the cold season — R_{HMT} no less than 15,4 MPa (80% of the project strength class);
– in the warm season — R_{HMT} no less than 13,4 MPa (70% of the project strength class).

The grade of the concrete mix for workability for the manufacture of lintels in compliance with the technology in use at the KSM 10 TD LLC plant was adopted to be P2. This is 5–9 cm while assessing the draft mobility of a standard cone concrete mix.

The consumption of materials per 1 cubic meter of the concrete mixture for manufacturing the lintels is shown in Table 1.

Table 1

Consumption of materials

Material type	Measurement unit	Amount
Cement CEM I 42.5	kg/m^3	260
Quartz sand	kg/m^3	750
Crushed stone fraction of 5–20 mm	kg/m^3	1200
Water	l/m^3	190
Superplasticizer additive ST BV2, %	%/kg/m^3	2.0/5.6

Portland cement with no additives was used as a binder, a normally hardening cement I 42.5/NW, which is in compliance with the requirements of GOST 55224-2020 produced at the Eurocement plant of JSC Mordovcement.

Quarry quartz sand with a grain size modulus was used as a fine aggregate. M_{GS} = 1.1.

The major characteristics of sand are

– packed density in dry condition — 1530 kg/m^3;
– the content of pulverized and clay particles — 5.2 %;
– the grain size modulus of the sand — 1.1.

The supplied sand is overall in compliance with the requirements of GOST 8736, according to the size of the sand it is very fine sand.

There are no harmful impurities in the sand, the PH exceeds the limits permitted by GOST (for very small ones — no more than 5%).

Sand can be used for preparing concrete mixtures in compliance with the provisions of GOST 26633 if its effectiveness is confirmed by direct tests in concrete.

A large aggregate — local crushed sandstone — is delivered to the enterprise by rail in the form of a fraction of 5–20 mm. The materials are in compliance with the requirements of GOST 26633.

The major characteristics of crushed stone:

– actual density — 2.67 g/cm^3;

– packed density — 1.46 t/m^3;

– emptiness — 45.3 %;

– water absorption — 1.2 %.

The content of pulverized and clay particles is 0.40%; of grains of weak rocks — 0.3%; of grains of the lamellar and needle shape — 10.73%; no clay in lumps. The content of amorphous SiO_2 species is 17.6 mmol/l; the content of sulfides and sulfates in terms of SO_3 is 0.07%; the content of halides in terms of chlorine ion Cl is 0.02%. The grade of crushed stone 1000 in terms of strength (crushing capacity in a cylinder) enables one to prepare concretes of class B10; B15; B20; B22.5; B27.5. The grade of crushed stone in terms of frost resistance is F200, abrasion resistance is I-1. The content of natural radionuclides Aeff in the filler is 115 ± 15 Bq/kg.

In order to produce concrete mixtures at the existing enterprise of LLC TD KSM 10, a complex chemical additive is used — superplasticizer ST BV2 with the effect of accelerating hardening. The supplier of the additive is LLC Concrete Construction Solutions, St. Petersburg. In compliance with the recommendations of the additive manufacturer, its major application area is for reinforced concrete and concrete structures hardening under heat treatment conditions. The additive does not reduce the protective properties of concrete in relation to steel reinforcement. The additive is delivered by road in the form of a liquid from a transparent yellow to a light brown color of a 30% concentration. Superplasticizer ST BV2 is introduced into concrete and mortar mixtures in the form of a working solution in the amount of 0.1–1.2% of the cement weight in terms of dry matter.

Water (clean tap water) is supplied to the enterprise from the city’s water supply network. The water used for mixing concrete and mortar mixtures does not contain harmful impurities interfering with the normal setting and hardening of cement and is in compliance with the requirements of GOST 23732.

In order to obtain data comparable to the literature, as well as to the basic production one, standard methods of testing materials and concrete samples were employed.

Technologies for improving the methods of preparing concrete mixtures, including those based on low-quality aggregates, have been thoroughly investigated by scholars at home and overseas [14–16]. The key reason why the results of these studies have not been widely communicated is the need for extra costs for technical re-equipment of the existing construction industry enterprises.

On top of that, the suggested methods are typically characterized by an increase in the duration of homogenization of a mixture and a decrease in the productivity of concrete mixers and concrete mixing plants.

Once a two-stage method of preparing concrete mixtures was developed without any of these disadvantages with Ye.A. Shlyakhova’s direct involvement. It was about pretreatment of aggregates with a high content of polluting dusty clay particles in the concrete mixer with a part of the mixing water adding a surfactant from the production of pentaerythritol from the Rubezhansky Chemical plant. As there was the issue of import substitution to deal with, one of the objectives of these studies was to look into the possibility of replacing pentaerythritol waste with available surfactant additives, mostly the ST BV2 superplasticizer used in basic production.

In order to obtain comparative data, the concrete mixtures being investigated were prepared by means of the traditional one-stage mixing method and the two-stage method being developed. The molded compared samples, beams measuring 40 × 40 × 160 mm after a two-hour pre-exposure, were subjected to heat and humidity treatment with an isothermal exposure temperature of 80 °C in compliance with the basic production regime.

For samples with optimal item-by-item consumption of the investigated components of the concrete mixture, a stepwise schedule of heat and moisture treatment was developed, providing for an intermediate period of concrete exposure. The two-stage schedule of heat and moisture treatment was made up of a few stages lasting for as long as it is shown in Table 2.

Table 2

Main parameters of heat and humidity treatment

Parameters	Designation	Value
Duration of the preliminary exposure (at t = 20–25 ºC), h	τ_{exp}	2
Isothermal heating temperature, ºC	t_{is}	80
Temperature rise rate, ºC/h	v	15–20
Duration of the temperature rise period (1 step of HMT), h	τ^1_p	1
Isothermal heating temperature (1 step of HMT), ºC	t^1_{is}	40
Duration of isothermal heating (1 step of HMT), h	τ^1_{is}	1
Duration of the temperature rise period (2 step of TMT), h	τ^2_p	2
Isothermal heating temperature (2 step of HMT), ºC	t^2_{is}	80
Duration of isothermal heating (2 step of HMT), h	τ^2_{is}	4
duration of cooling after HMT, h	τ_{cool}	2
concrete temperature after cooling, ºC	t_{cool}	40

Research Results. The effectiveness of the suggested two-stage method for preparing the concrete mixtures was experimentally confirmed. The traditional one-step method was employed as a control (basic) method. The research results are shown in Table 3.

Table 3

Results of a comparative assessment of the methods of preparation of concrete mixtures for the concrete lintels

Concrete mixture preparation method	Material consumption, kg/m³ / %				Additive dosage, % C / kg/m³	HMT mode	Compressive strength, MPa / % B15	
	C	S	CS	W			after HMT	after 28 days
Basic	260/100	750/100	1200/100	190/100	0.8/2.0	basic	13.6/71	19.6/102
Two-stage: I step	0	750/100	1200/100	75/40	0.2/0.5	basic	15.2/78	22.8/116
II step	260/100	0	0	115/60	0.6/1.5			
Two-stage: I step	0	750/100	1200/100	70/40	0.2/0.4	stepwise	14.3/73	20.1/105
II step	220/85	0	0	110/60	0.6/1.3			

As can be seen from the data in Table 3, the use of the two-stage method for preparing a concrete mixture enhanced the strength of concrete after HMT by 7% (from 13.6 to 15.2 MPa) and by 14% at the age of 28 days (from 19.6 to 22.8 MPa). This served as the basis for reducing cement consumption by 15% (from 260 to 220 kg/m^3) and the total consumption of superplasticizer additives from 2.0 to 1.7 kg/m^3 without any loss of strength compared to the basic version both after HMT and at the age of 28 days.

Discussion and Conclusion. The essence of the developed two-stage method of preparing a concrete mixture for basic products is that at the first stage of preparing the concrete mixture, the aggregates are mixed with some of the mixing water and the additives ST BV2 in the concrete mixer. At the second stage, cement, the remainder of the mixing water and superplasticizer additives are added to this mixture, then all of the components are finally mixed until there is a homogeneous concrete mixture of the required workability.

As a result of the experimental studies with a quite broad range of mixing water consumption and superplasticizer additives, optimal values of these factors were identified at each stage of the concrete mix preparation: at the first stage, 40% of the total mixing water consumption and 0.2% of the ST BV2 additive (based on anhydrous substance) from the cement mass were introduced; at the second stage of the preparation of the concrete mixture, the remainder of the mixing water and additives was introduced.

The products were manufactured by means of an aggregate-flow production technology using standard technological equipment. The concrete mix was delivered using a factory mixer with a volume of 5 m^3. The height of unloading of the concrete mix was no more than 100 cm in order to avoid its stratification and deterioration of technological properties.

For heat and moisture treatment of the products, a pit steaming chamber was used with heated steam supplied as a coolant from an external boiler room. The full cycle of hardening processes consisted of a stepwise temperature rise with periods of initial and intermediate exposure of the concrete mixture, followed by a period of isothermal exposure of the products at a maximum temperature of 80°C. This technique enabled the neutralization of the unevenness of the temperature field along the cross-section of the product, thus stabilizing the kinetics of chemical reactions and considerably reducing destruction in the material structure. Heat and moisture treatment was performed until 70% of the design strength of the concrete was reached.

In general, the technological flowchart of the two-stage method of preparing the concrete mixture for basic products is shown in Fig. 1.

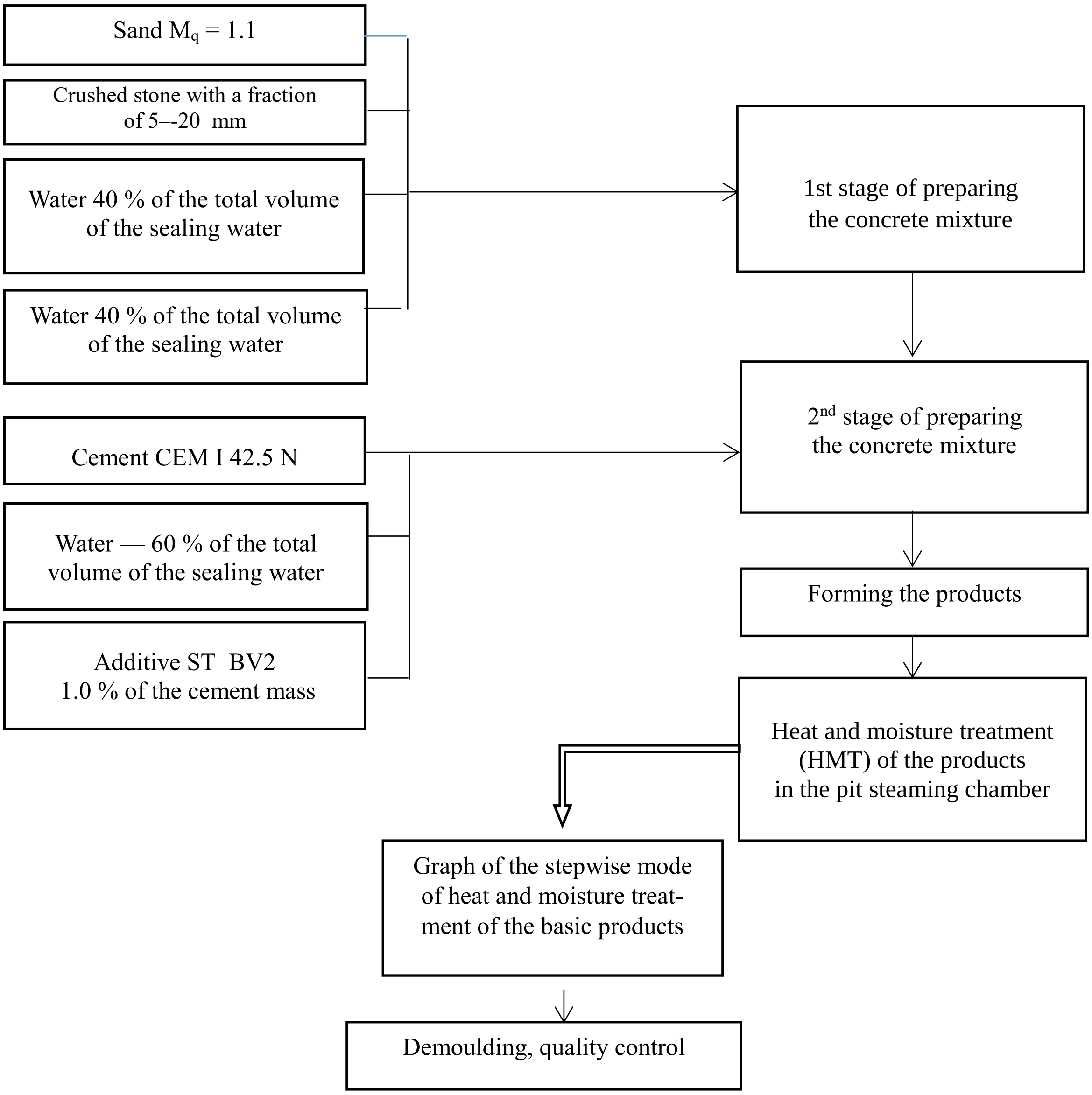


Fig. 1. Block diagram of a two-stage method for preparing the concrete mix for the factory-made reinforced concrete products

The methods developed in compliance with the research aim, which is to increase the efficiency of precast reinforced concrete technology using the example of the production of lintels for covering window and door openings of residential, civil and industrial buildings, enabled us to reduce the cement consumption by 15% and cut down by 0.3 kg/m^3 the superplasticizer consumption at the existing construction industry enterprises with no additional costs for reconstruction and technical re-equipment.

The suggested methods for increasing the efficiency of production technology are readily applicable to most precast reinforced concrete products and structures. At the same time, in each specific case, it is necessary to adjust the formulation and technological solutions accounting for the product requirements, the local raw material base and the specifics of the existing enterprise. Such an adjustment can be made with the forces and the factory laboratory equipment.

Apart from the direct economic effect at the construction industry enterprise, the suggested methods would contribute to improving the ecological state of the environment and reducing the cost of enriching local aggregates and disposing of the waste.

References

1. Fotin OV Construction of Precast Reinforced Concrete. *Building Materials*. 2023;4:32–34, (In Russ.) https://doi.org/10.31659/0585-430X-2023-812-4-32-34

2. Davidyuk AN Concrete in Construction - New Challenges and Prospects. *Bulletin of NIC Construction*. 2017;1(12):5–13. (In Russ.) URL: https://elibrary.ru/item.asp?edn=YINMWP&ysclid=m830uuh8d0610542454 (accessed: 14.04.2025).

3. Yelishev KS Formation of the Structure of Heavy Concrete for the Production of Wall Panels. *The Scientific Heritage*. 2021;78-1(78):13–15. (In Russ.) https://doi.org/10.24412/9215-0365-2021-78-1-13-15

4. Zelenkovskaya ZhL, Kovshar SN Purpose and Justification of Traditional Modes of Heat Treatment of Concrete and Reinforced Concrete Products. *Science & Technique*. 2023;22(2):150–157. (In Russ.) https://doi.org/10.21122/2227-1031-2023-22-2-150-157

5. Serebryanaya I, Egorochkina I, Shlyakhova E, Matrosov A Investigation of the Contact Zone Between Cement Stone and Various Types of Aggregates in Concrete. *Networked Control Systems for Connected and Automated Vehicles.* 2022;509:1615–1622. https://doi.org/10.1007/978-3-031-11058-0_164

6. Bazhenov YuM, Murtazaev S-AYu, Bataev DK-S High-strength concretes based on anthropogenic raw materials for earthquake resistant high-rise construction. *Engineering Solid Mechanics.* 2021;9(3):335–346. https://doi.org/10.5267/j.esm.2021.1.004

7. Dzhabarov AS, Belov VV Screening as an Alternative to the Used Aggregates for Concrete. *Building Materials*. 2024;5:28–33. (In Russ.) https://doi.org/10.31659/0585-430X-2024-824-5-28-33

8. Kurbatov VL, Pecheny BG, Kireev VG, Komarova ND Influence of Pollutants in Aggregates on the Properties of Concrete Mixtures and Concretes. *Modern Science-Intensive Technologies*. 2017;9:34–41. (In Russ.) URL: https://top-technologies.ru/ru/article/view?id=36797 (accessed: 14.04.2025).

9. Fediuk R, Mochalov A, Timokhin R Review of methods for activation of binder and concrete mixes. *AIMS Mater. Sci.* 2018;5(5):916–931. https://doi.org/10.3934/matersci.2018.5.916

10. Lotov VA, Sukharev EA, Kutugin VA Preliminary Activation of a Cement-Sand Mixture in Order to Increase the Strength of Concrete. *Izv. vuzov. Chemistry and Chemical Technology*. 2022;65(8):94–101. (In Russ.) https://doi.org/10.6060/ivkkt.20226508.6595

11. Ibragimov R, Fediuk R. Improving the early strength of concrete: Effect of mechanochemical activation of the cementitious suspension and using of various superplasticizers. *Construct. Build. Mater.* 2019;226:839–848. https://doi.org/10.1016/j. conbuildmat.2019.07.313

12. Velichko E, Polkovnikov N, Sadchikova Yu. Efficient concrete increased water resistance modified with mineral and polymeric additives. *E3S Web of Conferences*. 2019;97:02017. https://doi.org/10.1051/e3sconf/20199702017

13. Nesvetaev GV, Lopatina YuYu Design of Macrostructure of Self-Compacting Concrete and its Mortar Component. *Internet Magazine "Naukovedenie"* 2015;7(5). (In Russ.) http://dx.doi.org/10.15862/48TVN515

14. Shlyahova EA *Method of Preparing Concrete Mixture.* Patent RU 2714895 C1 (2020) (In Russ.)

15. Sakanov DK Effective Massive Aggregates for Top Layer of Concrete Pavement. *Problems of Modern Concrete and Reinforced Concrete.* 2016;8:213–224. https://doi.org/10.23746/2016-8-12

16. Kadyrova DSh Strength and Deformative Properties of Concrete Based on Local Raw Materials and Industrial Waste. *Modern Industrial and Civil Construction*. (In Russ.) 2021;17(2):93–101. URL: https://donnasa.ru/publish_house/journals/spgs/2021-2/03_kadyrova_saydullaev.pdf (accessed: 14.04.2025).

About the Authors:

Elena A. Shlyakhova, Cand.Sci. (Eng.), Associate Professor of the Department of Technological Engineering and Expertise in the Construction Industry at the Don State Technical University (162 Sotsialisticheskaya str., Rostov-on-Don, 344003, Russian Federation), ScopusID, ORCID, shlyahovae@list.ru

Inna O. Egorochkina, Cand.Sci. (Eng.), Associate Professor of the Department of Technological Engineering and Expertise in the Construction Industry at the Don State Technical University (162 Sotsialisticheskaya str., Rostov-on-

Don, 344003, Russian Federation), ScopusID, ORCID, arin77@bk.ru

Claimed contributorship:

EA Shlyakhova: development of the idea, aims and objectives of the study, calculations, analysis and drawing conclusions, manuscript preparation, revision of the manuscript.

IO Egorochkina: analysis of the research results, revision of the manuscript, correction of the conclusions, formation of the list of references.

Conflict of interest statement: the authors do not have any conflict of interest.

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

Об авторах:

Елена Альбертовна Шляхова, кандидат технических наук, доцент кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, ул. Социалистическая, 162), ScopusID, ORCID, shlyahovae@list.ru

Инна Олеговна Егорочкина, кандидат технических наук, доцент кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, ул. Социалистическая, 162), ScopusID, ORCID, arin77@bk.ru

Заявленный вклад авторов:

Е.А. Шляхова: формирование основной концепции, цели и задачи исследования, подготовка текста, формирование выводов.

И.О. Егорочкина: анализ результатов исследований, доработка текста, корректировка выводов, формирование списка литературы.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 20.04.2025
Reviewed / Поступила после рецензирования 14.05.2025
Accepted / Принята к публикации 30.05.2025

BUILDING MATERIALS AND PRODUCTS

СТРОИТЕЛЬНЫЕ МАТЕРИАЛЫ И ИЗДЕЛИЯ

Check for updates

UDC 691.3
https://doi.org/10.23947/2949-1835-2025-4-2-57-66

Original Empirical Research

EDN: NOGHXW

Investigation of the Factors Influencing the Effectiveness of Fine-Grained Self-Compacting Concrete with Crushed Concrete Sand

Lyubov I. Kastornykh ✉, **Alexander V. Kaklyugin**, **Mikhail G. Kholodnyak**, **Denis V. Kuzmenko**
Don State Technical University, Rostov-on-Don, Russian Federation
✉ likas9@mail.ru

Abstract

Introduction. The justified use of mineral raw materials from construction waste for the preparation of vibro-compacted concrete mixtures is economically beneficial and environmentally efficient, however, the effect of aggregates from scrap concrete on the rheological characteristics of fine-grained self-compacting mixtures and the structure of hardened concrete has not been sufficiently studied. The aim of this work is to study the factors influencing the effectiveness of fine–grained self-compacting concrete with crushed concrete sand.

Materials and Methods. To determine the effectiveness of the compositions of fine-grained self-compacting concretes, mixtures of equal workability of the PK1 grade were prepared on Portland cement CEM0 52.5N. Sand from crushed concrete was introduced into the fine natural sand of local quarries as a reinforcing component. Polyplast PC, a polycarboxylate superplasticizer, was used to give the mixtures the required fluidity and self–compacting properties. The evaluation of the grain composition of the fine aggregate was carried out by changing the grain size modulus in accordance with the standard methodology. Rheological and technological characteristics of self-sealing concrete mixtures were established according to the methods of GOST R 59715-2022. Crack resistance of fine-grained self-compacting concrete was assessed by a coefficient reflecting the ratio of strength characteristics of concrete.

Results. Throughout the course of the research, it was found that, provided a highly stable concrete mixture is obtained, the optimal structure of fine-grained concrete is achieved with a content of 30% crushed concrete grains in the fine aggregate and a dosage of polycarboxylate superplasticizer Polyplast PC – 1%.

Discussion and Conclusion. The technical efficiency of fine-grained self-compacting concrete using coarsening sand grains from crushed concrete is substantiated. By optimizing the formulation factors of fine-grained concrete with aggregate from construction waste and using vibration-free technology of monolithic reinforced concrete structures made of self-compacting mixtures, an economic effect is ensured.

Keywords: fine-grained self-compacting mixtures, sand from crushed concrete, polycarboxylate superplasticizer, stability of the concrete mix, crack resistance of fine-grained concrete

Acknowledgements. The authors appreciate the reviewers, whose critical assessment of the submitted materials and suggestions helped to significantly improve the quality of this article.

For citation. Kastornykh LI, Kaklyugin AV, Kholodnyak MG, Kuzmenko DV. Investigation of Factors Influencing the Effectiveness of Fine-Grained Self-Compacting Concrete with Crushed Concrete Sand. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):57–66. https://doi.org/10.23947/2949-1835-2025-4-2-57-66

Оригинальное эмпирическое исследование

Исследование факторов, влияющих на эффективность мелкозернистого самоуплотняющегося бетона с песком из дроблёного бетона

Л.И. Касторных ✉, **А.В. Каклюгин**, **М.Г. Холодняк**, **Д.В. Кузьменко**
Донской государственный технический университет, Ростов-на-Дону, Российская Федерация
✉ likas9@mail.ru

Аннотация
Введение. Обоснованное применение минерального сырья из строительных отходов для приготовления виброуплотняемых бетонных смесей экономически выгодно и экологически эффективно, однако влияние заполнителей из бетонного лома на реологические характеристики мелкозернистых самоуплотняющихся смесей и структуру затвердевшего бетона изучено недостаточно. Цель настоящей работы — исследование факторов, влияющих на эффективность мелкозернистого самоуплотняющегося бетона с песком из дроблёного бетона.
Материалы и методы. Для определения эффективности составов мелкозернистых самоуплотняющихся бетонов готовили смеси равной удобоукладываемости марки РК1 на портландцементе ЦЕМ0 52,5Н. В качестве укрупняющего компонента в состав мелкого природного песка местных карьеров вводили песок из дроблёного бетона. Для придания смесям требуемой текучести и самоуплотняемости применяли добавку Полипласт ПК — поликарбоксилатный суперпластификатор. Оценку зернового состава мелкого заполнителя проводили по изменению модуля крупности в соответствии со стандартной методикой. Реологические и технологические характеристики самоуплотняющихся бетонных смесей устанавливали по методикам ГОСТ Р 59715-2022. Трещиностойкость мелкозернистого самоуплотняющегося бетона оценивали по коэффициенту, отражающему соотношение прочностных характеристик бетона.
Результаты исследования. В ходе исследований установлено, что при условии получения высокостабильной бетонной смеси оптимальная структура мелкозернистого бетона достигается при содержании в составе мелкого заполнителя 30 % зерен дробленого бетона и дозировке поликарбоксилатного суперпластификатора Полипласт ПК — 1 %.
Обсуждение и заключение. Обоснована техническая эффективность мелкозернистого самоуплотняющегося бетона с использованием укрупняющих зерен песка из дробленого бетона. За счет оптимизации рецептурных факторов мелкозернистого бетона с заполнителем из строительных отходов и применения безвибрационной технологии монолитных железобетонных конструкций из самоуплотняющихся смесей достигается экономический эффект.

Ключевые слова: мелкозернистые самоуплотняющиеся смеси, песок из дроблёного бетона, поликарбоксилатный суперпластификатор, стабильность бетонной смеси, трещиностойкость мелкозернистого бетона

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

Для цитирования. Касторных Л.И., Каклюгин А.В., Холодняк М.Г., Кузьменко Д.В. Исследование факторов, влияющих на эффективность мелкозернистого самоуплотняющегося бетона с песком из дроблёного бетона. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):57–66. https://doi.org/10.23947/2949-1835-2025-4-2-57-66

Introduction. The key factors for technical and economic efficiency of vibro-compacted concrete are the type, consumption and quality of materials. The most efficient one is the grain composition of the aggregate, as it is the granulometry of the aggregate determining the water consumption and that of the binder in the concrete mixture and is thereby responsible for its cost [1].

For self-compacting concrete mixes, not only are the granulometric characteristics of the aggregate critical, but also the shape of its grains. While choosing the type of filler, materials with a rounded particle shape that ensures free flow and self-sealing of the mixture should be preferred [2].

The use of mineral raw materials from "old" concrete for preparing concrete mixes is due to the regulatory documentation and numerous studies validating the technical and environmental effects of recycling construction waste [3–6]. Crushing and screening plants are used for obtaining coarse and fine aggregate from concrete scrap, which contribute to the formation of a highly developed clastic rough shape of aggregate grains [7]. The use of such a material for self-compacting concrete mixtures should be validated by preliminary studies [8–10].

For fine-grained self-compacting concrete mixtures (SCC) used for concreting thin-walled and densely reinforced structures, the granulometric characteristic of the aggregate also plays a key role in ensuring the required fluidity. In some cases, in order to obtain high-strength concrete, an enlarging component should be added to the fine aggregate. As an enlarging additive for optimization of the grain composition of fine aggregate, natural crushed stone screening and construction waste recycling products are traditionally used [11–13] according to GOST 31424-2010 "Non-Metallic Building Materials from Dense Rock Crushing in the Production of Crushed Stone". The role of large grains of sand from crushed concrete on the formation of the structure of self-compacting concrete has not been sufficiently investigated. Therefore the aim of this work was to examine the factors affecting the efficiency of fine-grained self-compacting concrete with crushed concrete sand.

Materials and Methods. A fine filler was used which included:

– natural sand (hereinafter S_{NAT}) in compliance with the requirements of GOST 8736-2014 "Sand for Construction Work": true density is 2650 kg/m^3; bulk density is 1410 kg/m^3; modulus of fineness is 1.15 (group — very fine); voidness is 46.6 %;

– crushed concrete sand (hereinafter S_{CR}) in compliance with the requirements of GOST 32495-2013 "Crushed Stone, Sand and Sand-Crushed Stone Mixtures from Crushed Concrete and Reinforced Concrete", mixtures of three fractions: 0.63–1.25 mm, 1.25–2.5 mm, 2.5–5.0 mm in a weight ratio of 20:30:50, respectively. The optimal ratio of sand fractions from crushed concrete was identified according to the results of previous studies [14].

Fine-grained concrete mixtures were prepared using an additive—free Portland cement type CEM0 52.5N, which is in compliance with the requirements of GOST 31108-2020 "General Construction Cements": compressive strength at the age of 28 days — 63.3 MPa; compressive strength after heat treatment — 48.2 MPa; normal density of cement dough — 27.8%; specific surface area — 382.5 m^2/kg; the start of the setting time — 90 min.

In order to ensure self-compaction and required fluidity of the concrete mix, a Polyplast PC superplasticizer (hereinafter SP PC) based on polycarboxylate esters was used. The additive, which is universal for commercial concrete mixes and precast reinforced concrete, is used according to the manufacturer's recommendations to regulate the retention of mixtures while rapidly gaining early concrete strength. The dosage range of the chemical modifier for fine-grained concrete mixtures was identified based on previous studies [15–17].

The grain composition of the aggregate while adding coarsening grains from crushed concrete was evaluated by changing the size modulus in compliance with the GOST 8735-88 "Sand for Construction Work" method.

Rheological and technological characteristics of fine-grained concrete mixtures were identified according to the methods of GOST R 59715-2022 "Self-Compacting Concrete Mixtures". The mixture was evaluated according to the indicators of self-compacting *PK* and fluidity *F* using a locking ring with 16 rods (Fig. 1).

Fig. 1. Device for identifying the self-compaction and fluidity of the concrete mixtures

The viscosity of the fine-grained t_{500} mixture was identfiied by recording the time the mixture took to first touch the 500-millimeter circle mark throughout its spreading.

In order to assess the stability of the mixture (resistance to delamination), the VSI index was used calculated by means of the visual method throughout its spreading.

In order to identify the physico-mechanical characteristics of fine-grained self-compacting concrete, control samples were prepared using a mixture of each composition-cubes with a nominal rib size of 100 mm.The concrete samples were produced, stored and tested in compliance with the GOST 10180-2012 "Concretes" methodology.

The crack resistance of fine—grained concrete was assessed by the coefficient K_{cr}, an indirect characteristic reflecting the ratio of concrete flexural strength to compressive strength [10, 18]:

$$K_{cr} = R_{bt}/R_b,$$

where R_{bt} is the bending strength of concrete, MPa; R_b is the compressive strength of concrete, MPa.

The structural characteristics of fine-grained concrete were assessed from micrographs of a sample section taken in polarized light using an optical microscope with a LEVENHUK C310 camera (the field of view diameter is 18 mm; spectral range is 400–650 nm; active range is 75 dB; sensitivity is 1.5 nm; maximum resolution is 2048×1536).

Research Results. Through the course of the study, the granulometric composition of fine aggregates was analyzed while using sand from crushed concrete as an aggregating additive (Table 1).

Table 1

Analysis of the granulometric composition of fine aggregates

Type and composition of the filler, %	Name of the residue	Residue, % by mass, on the sieves sized, mm					Passage through a sieve with a grid N016, % by mass	Fineness modulus
		2.5	1.25	0.63	0.315	0.16		
$\frac{П_{пр}}{100}$	Particular	0.03	0.10	0.405	27.505	58.00	13.96	1.15
	Complete	0.03	0.13	0.535	28.040	86.04	100.0	
$\frac{П_{пр} + П_{др}}{80 + 20}$	Particular	8.615	5.235	3.760	23.060	44.685	14.645	1.66
	Complete	8.615	13.85	17.61	40.670	85.355	100.0	
$\frac{П_{пр} + П_{др}}{70 + 30}$	Particular	12.60	7.605	4.220	21.820	40.030	13.725	1.90
	Complete	12.60	20.205	24.425	46.245	86.275	100.0	
$\frac{П_{пр} + П_{др}}{60 + 40}$	Particular	16.81	10.16	6.420	20.775	34.900	10.935	2.20
	Complete	16.81	26.97	33.39	54.165	89.065	100.0	

The studies have shown that the natural sand of local quarries, belonging to the group of very small ones, contributes to an increase in water consumption and cement consumption in concrete mixes. Thus its use is possible only after substantiating tests in concrete. While enriching natural sand with crushed concrete grains in the range from 20 to 40%, the granulometric characteristic of the aggregate is improved by increasing the number of grains measuring 0.63–5.0 mm.

In order to assess the effect of the grain composition of the aggregate on the basic properties of fine-grained self-sealing mixtures and concretes based on them, PK1 grade workability mixtures (cone spreadability 55–65 cm according to GOST R 59714-2021 "Self-Compacting Concrete Mixtures") were prepared with a nominal cement consumption of 510 kg/m^3. While the spreadability of the mixture was being identified, so were its viscosity, fluidity and stability.

The following factors were taken as those impacting the rheological and physico-mechanical properties of self-compacting materials:

– the grain content of crushed concrete in the natural fine aggregate ranges from 20 to 40% with an interval of 5%;

– the dosage of the superplasticizer SP PK in the range from 0.5 to 1.5% of the cement weight with a range of 0,5%.

The composition and rheological characteristics of the concrete mixtures are in Table 2. The dependence of the viscosity and fluidity of the mixtures on the composition of the filler and the dosage of the superplasticizer are shown in Fig. 2 and 3, respectively.

Table 2

Characteristics and stability assessment of the fine-grained concrete mixtures

Composition	Content of S_{cr}, %	Dosage of SP SK, %	W/C	Viscosity, s	Fluidity, mm	Average density, kg/m^3	Visual characteristics of the mixture	Stability index VSI according to GOST R 59715
1FC	20	1.0	0.49	5.3	25.0	2128	Homogeneous, but gets thick fast	1 — stable
2FC	25	1.5	0.49	6.0	25.5	2185	A light residue on the mixture surface	2 — unstable
3FC	25	0.5	0.69	2.0	10.5	2082	Homogeneous, but fluids at once	1 — stable
4FC	30	1.0	0.49	6.5	26.5	2145	Homogeneous, flows well	0 — highly stable
5FC	35	1.5	0.45	4.4	17.5	2215	A light residue on the mixture surface	2 — unstable
6FC	35	0.5	0.54	2.0	23.0	2195	Homogeneous, but fluids at once	1 — stable
7FC	40	1.0	0.47	2.8	14.5	2208	Noticeable water separation of the mixture	3 — highly unstable

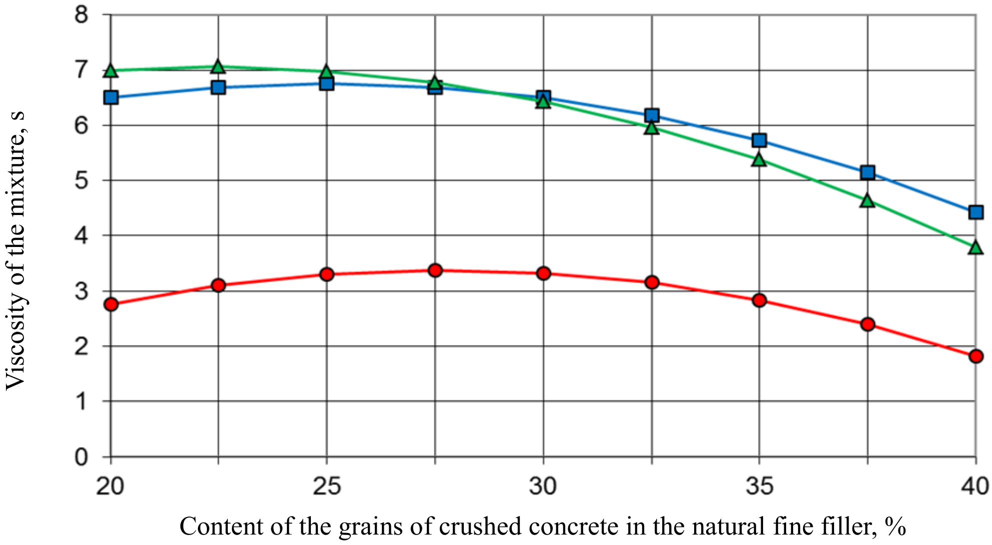


Fig. 2. Dependence of the viscosity of mixtures on the composition of the filler and the dosage of the superplasticizer: ○ — dosage of SP PK 0.5%; □ — dosage of SP PK 1.0%; Δ — dosage of SP PK 1.5 %

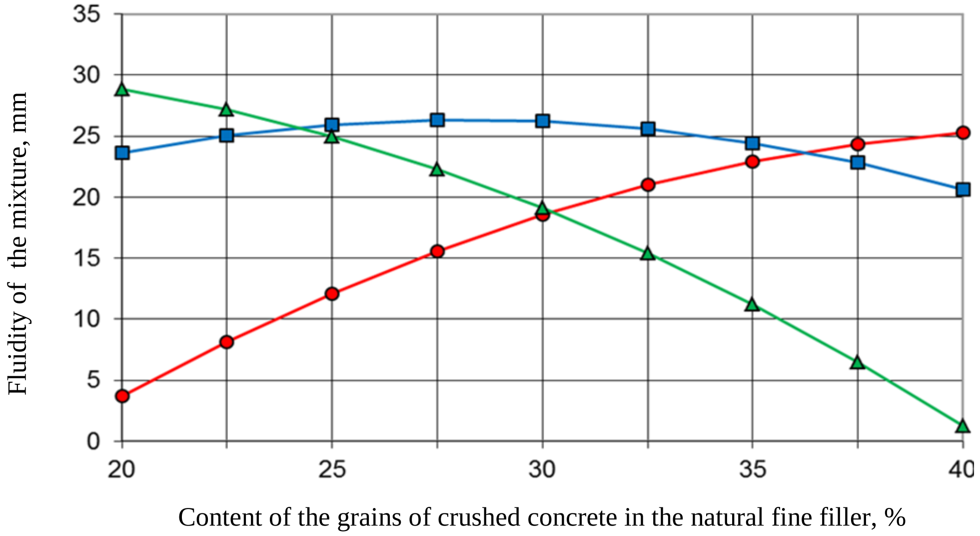


Fig. 3. Dependence of the viscosity of mixtures on the composition of the filler and the dosage of the superplasticizer: ○ — dosage of SP PK 0.5%; □ — dosage of SP PK 1.0%; Δ — dosage of SP PK 1.5%

Throughout the course of the study, it was found that in order to obtain stable self-sealing fine-grained mixtures, the dosage of crushed sand should be no more than 30% (composition 4FC). An increase in the number of grains with a rough, developed surface shape inevitably causes delamination of the mixture, and an increase in the dosage of the superplasticizer enhances this causing noticeable water separation.

An analysis of the dependence of the rheological characteristics of fine-grained mixtures on the composition of the filler and the dosage of the superplasticizer shows that as the proportion of large grains of sand from crushed concrete increases, the viscosity of the mixtures decreases, and the fluidity changes ambiguously. An increase in the yield index was observed as the consumption of large grains in formulations with a minimum dosage of superplasticizer was rising. In the compositions with the maximum dosage of SP PK, on the contrary, there is a decrease in the fluidity of mixtures as the proportion of the enlarging additive in the composition of the sand was rising. This type of change in the fluidity of mixtures validates the significant influence of the grain composition of the filler on the rheological properties of self-compacting mixtures. For these compositions, a highly stable, homogeneous, non-delaminating mixture was obtained with the consumption of crushed sand grains in the aggregate in an amount of 30% and a dosage of SP PK — 1.0%.

The structural parameters and physico-mechanical characteristics of fine-grained self-compacting concrete of the compositions are in Table 3. The effect of aggregate composition and superplasticizer dosage on the strength of fine-grained concrete tested at early (1 day) and design (28 days) ages is shown in Fig. 4.

Table 3

Design indicators and physico-mechanical characteristics of the self-compacting materials

Composition	Consumption of materials per 1 m^3, kg			W/C	Average density of concrete, kg/m^3	Strength limit, MPa		Coefficient K_{CR}
	S_{nat}	S_{CR}	SP PK			compressive	under bending	
1FC	1093	274	5.1	2.04	2116	46.1	6.46	0.140
2FC	1052	351	7.4	2.04	2126	48.6	5.51	0.113
3FC	960	319	2.7	1.45	2068	33.1	4.30	0.129
4FC	965	414	5.1	2.04	2156	52.6	6.37	0.121
5FC	933	502	7.6	2.22	2179	55.4	6.10	0.110
6FC	907	488	2.9	1.85	2157	45.9	4.63	0.101
7FC	855	570	5.3	2.13	2182	52.6	7.08	0.135

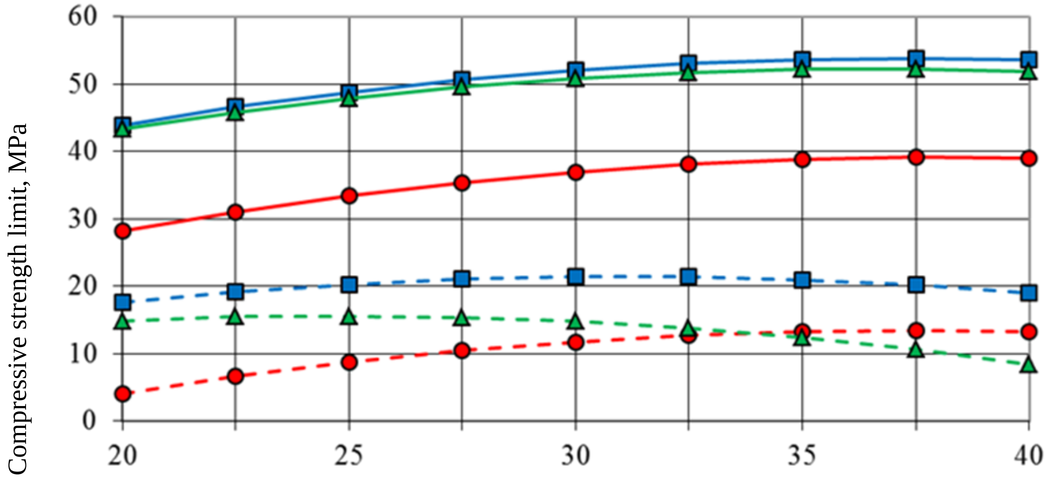


Fig. 4. Dependence of the strength of mixtures on the composition of the filler and the dosage of the superplasticizer:
○ — dosage of SP PK 0.5%; □ — dosage of SP PK 1.0%; Δ — dosage of SP PK 1.5%;
- - - - — concrete strength at the age of 1 day; —— — concrete strength at the age of 28 days

An analysis of the data shows that the effect of the consumption of coarsening grains and the dosage of the superplassifier on the formation of the initial structural strength of concrete is insignificant. For concretes tested at the design age, it was found that an increase in the content of large grains of sand from crushed concrete in the range from 32.5 to 40% causes that in compressive strength by 25%. At the same time, the maximum strength of concrete is fixed for compositions with the maximum dosage of the superplasticizer.

The influence of compounding and technological factors on the crack resistance of fine-grained self-sealing concrete is shown in Fig. 5. It has been found that as the content of coarse grains of crushed sand in the aggregate increases, the coefficient of crack resistance of concrete CTE changes non-linearly. The formation of a fine-grained concrete structure capable of resisting the development of cracks is associated with the rational granulometric composition of the aggregate and the optimal content of cement stone.

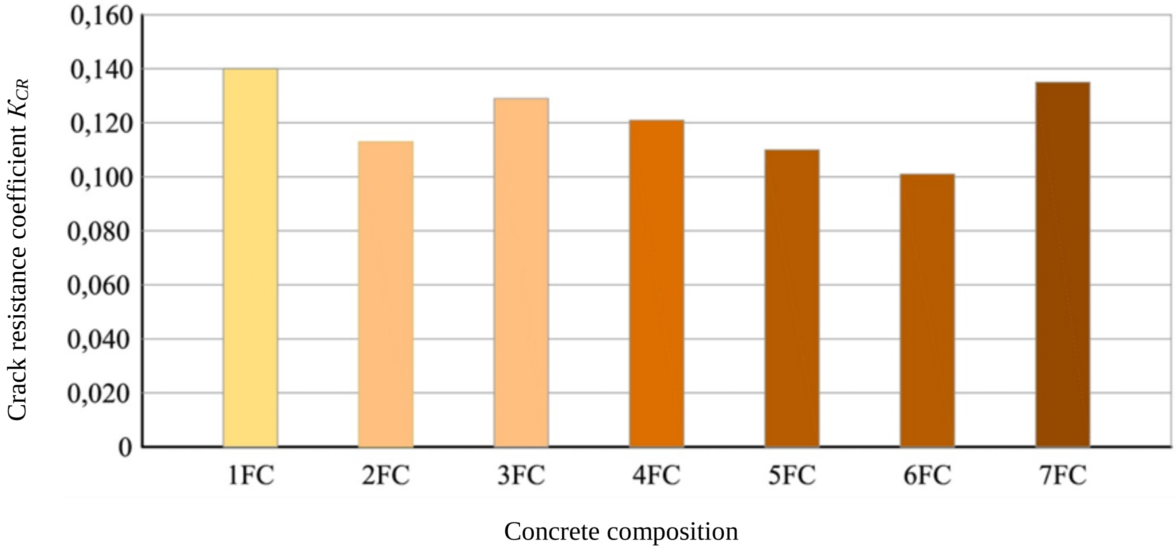
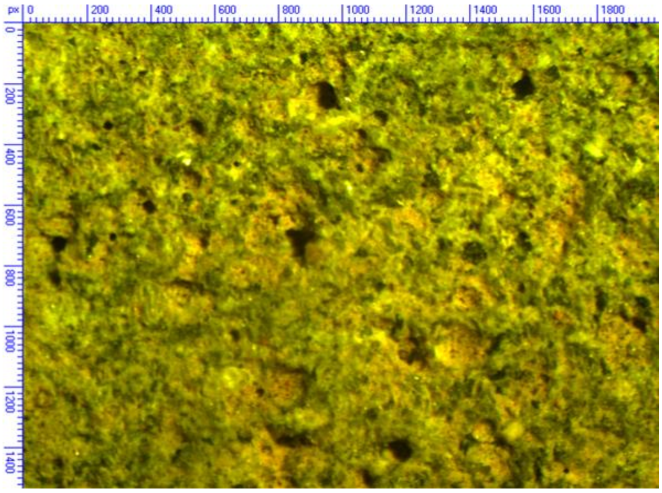
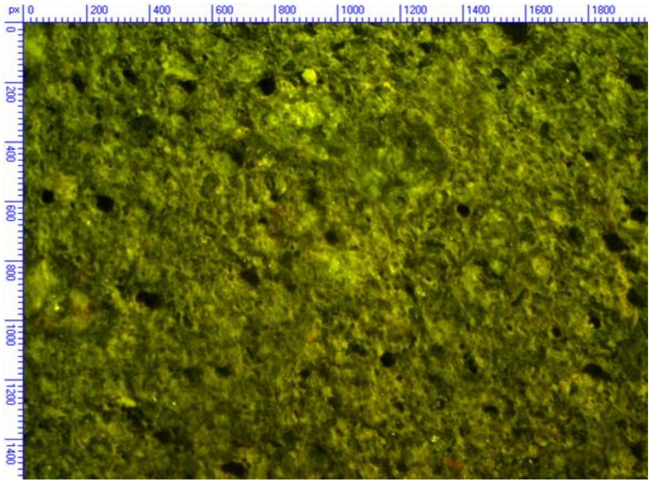


Fig. 5. Dependence crack resistance coefficient of the self-compacting materials on prescription factors

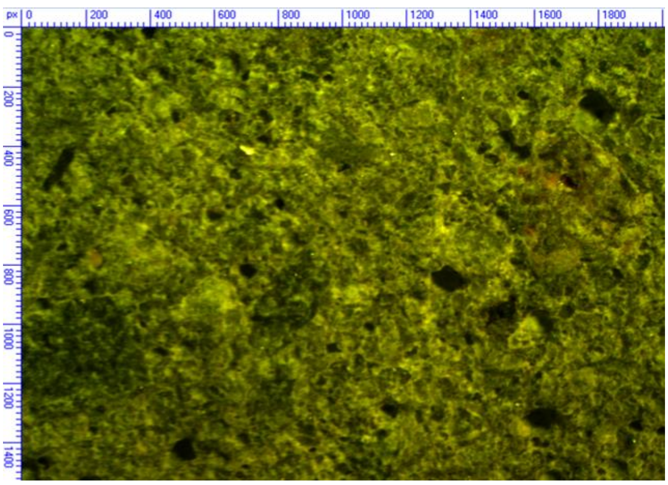
Fig. 6 shows micrographs of a section of self-compacting materials samples, clearly showing the structure of concrete with different concentrations of coarse grains of sand from crushed concrete.



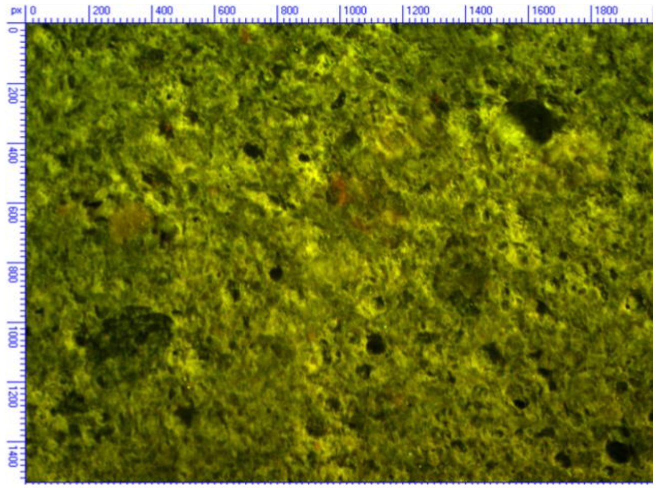
a)



b)



c)



d)

Fig. 6. Micrographs of a section of self-compacting materials samples containing crushed sand grains:
a — 20%; *b* — 25%; *c* —30%; *d* — 40%

In this study, it was found that, provided a highly stable mixture is obtained, the optimal structure of fine-grained concrete is attained when the aggregate contains 30% large grains of crushed concrete and a dosage of SP PK — 1% (composition 4FC in Fig. 6 *c*).

Discussion and Conclusion. The studies have shown that the enrichment of natural fine sand from local quarries with grains of 0.63–5.0 mm from crushed concrete sand in an optimal amount enhances the granulometric composition of the aggregate and with no loss of the fluidity of the mixture, increases the strength of concrete. It has been revealed that prescription factors have a significant impact on the rheological parameters of fine-grained self-compacting mixtures. In order to obtain stable mixtures characterized by cohesiveness and non-delamination, the proportion of large grains of crushed sand in the aggregate composition should not b be over 30%, and the dosage of polycarboxylate superplasticizer should be 1.0% by weight of cement.

The analysis of the strength characteristics of fine-grained self-compacting concretes with crushed concrete sand has shown that the formation of a rational structure is related to that of the mixture and the technology of its transportation and laying. The use of vibration-free concrete pump technology in the construction of monolithic reinforced concrete structures made of self-compacting mixtures with sand from construction waste will help one reduce the estimated cost of work and improve the environmental situation in the Don region [14, 19].

References

1. Bazhenov YuM, Chernyshov EM, Korotkikh DN Designing of Modern Concrete Structures: Determining Principles and Technological Platforms. *Building Materials*. 2014;3:6–14. (In Russ.) https://cyberleninka.ru/article/n/konstruirovanie-struktur-sovremennyh-betonov-opredelyayuschie-printsipy-i-tehnologicheskie-platformy (accessed: 29.03.2025)

2. Kastornykh LI, Cherepanov VD, Berezovoy VE Optimization of Grain Composition of Aggregate for Fine-Grained Self-Compacting Concrete. *Young Researcher of the Don*. 2020;5(26):40–48. (In Russ.) https://www.elibrary.ru/item.asp?id=44048323

3. Larsen OA, Narut VV, Voronin VV Technology of Processing Concrete Scrap in Order to Obtain Self-Compacting Concrete. *Construction and Reconstruction*. 2020;2(88):61–66. (In Russ.) https://doi.org/10.33979/2073-7416-2020-88-2-61-66

4. Buldyzhov AA, Alimov LA Self-Compacting Concretes with Nanomodifiers Based on Technogenic Waste. *Industrial and Civil Construction*. 2014;8:86–88. (In Russ.).

5. Krasinikova NM, Kirillova EV, Khozin VG Recycling of Concrete Scrap as Raw Materials of Cement Concretes. *Building Materials*. 2020;1-2:56–65. (In Russ.) https://doi.org/10.31659/0585-430X-2020-778-1-2-56-65

6. Kastornykh L, Kosenko V, Kaklyugin A, Kholodnyak M, Fedorchenko A Vibration–Free Decorative Concrete Technology is the Key to Sustainable Development of Landscape Architecture. *Lecture Notes in Networks and Systems*. 2023;575. https://doi.org/10.1007/978-3-031-21219-2_328

7. Lopatin NA, Motornaja AI, Neguliaeva EYu The Most Effective Crushing Equipment and Testing of Recycled Concrete Aggregates. *Construction of Unique Buildings and Structures*. 2015;10(37):34–45. URL: https://unistroy.spbstu.ru/userfiles/files/2015/10(37)/3_lopatin_37.pdf (accessed: 29.03.2025).

8. Pulyaev SM Research of Early Structure Formation Process of Concrete Where Concrete Waste are Used as Crushed Stone. *Bulletin of the Moscow State University of Civil Engineering*. 2012;1:68–71. (In Russ.) URL: https://cyberleninka.ru/article/n/issledovanie-protsessa-rannego-strukturoobrazovaniya-betona-na-schebne-iz-betonnogo-loma-1 (accessed: 29.03.2025).

9. Alwaeli M, Alshawaf M Waste Utilization in Concrete Technology as a Substitute for Natural Aggregates in the Context of Circular Economy: an Overview. *19th International Multidisciplinary Scientific GeoConference SGEM 2019*. 2019;19: 151–158. https://doi.org/10.5593/sgem2019V/4.2/S05.021

10. Kastornykh L, Kaklyugin A, Kholodnyak M, Osipchuk I Modified Concrete Mixes for Monolithic Construction. *Materials Science Forum: Materials and Technologies in Construction and Architecture IV*. 2021;1043:81–91. https://doi.org/10.4028/www.scientific.net/MSF.1043.81

11. Goncharova MA, Burkov PV, Al-Suraimi HGH Recycling of Large-Capacity Concrete and Reinforced Concrete Waste During the Implementation of Full-Life Cycle Contracts. *Building Materials*. 2019;12:52–57. (In Russ.) https://doi.org/10.31659/0585-430X-2019-777-12-52-57.

12. Modani PO, Mohitkar V Self-Compacting Concrete with Recycled Aggregate: a Solution for Sustainable Development. *International Journal of Civil Structural Engineering*. 2014;4:430–440.

13. Trischenko IV, Kastornykh LI, Fominych YuS, Gikalo MA Evaluation of Effectiveness of Investment Project of Reconstruction of Large-Panel Construction Enterprises. *Housing Construction*. 2018;10:39–43. (In Russ.) URL: https://cyberleninka.ru/article/n/otsenka-effektivnosti-investitsionnogo-proekta-rekonstruktsii-predpriyatiy-krupnopanelnogo-domostroeniya (accessed: 29.03.2025).

14. Kastornykh LI, Gikalo MA, Kaklyugin AV, Serebryanaya IA Mathematical Modeling the Processes of Concreting the Monolithic Structures Made of the Fine-Grained Mixes. *Modern Trends in Construction, Urban and Territorial Planning*. 2023;2(4):84–93. (In Russ.) https://doi.org/10.23947/2949-1835-2023-2-4-84-93

15. Smirnova OM Compatibility of Portland Cement and Polycarboxylate-Based Superplasticizers in High-Strength Concrete for Precast Constructions. *Magazine of Civil Engineering*. 2016;6:12–22. https://doi.org/10.5862/MCE.66.2

16. Kastornykh LI, Trischenko IV, Kakljugin AV, Shershen DR Heat Curing Efficiency Estimation of Concrete with Superplastificators on Polycarboxylates Basis. *Materials Science Forum: Materials and Technologies in Construction and Architecture II*. 2019;974:231–236. https://doi.org/10.4028/www.scientific.net/MSF.974.231.

17. Murtazaev YuS-A, Sheina SG, Murtazaev IS-A, Mezhidov D.A. Self-sealing concretes using chemical additives based on polyacrylic esters and polycarboxylates. *Bulletin of GGNTU. Technical sciences*. 2023;Vol.XIV,1(31):88–95. (In Russ.) https://doi.org/10.34708/GSTOU.2023.74.53.009

18. Travush VI, Karpenko NI, Erofeev VT, Erofeeva IV, Tarakanov OV, Kondrashenko VI, Kesariyskiy AG The study of crack resistance of new generation concrete. *Building Materials*. 2019;10:3–11. (In Russ.) https://doi.org/10.31659/0585-430X-2019-775-10-3-11

19. Larsen OA, Samchenko SV., Narut VV, Aleksandrova OV, Bulgakov BI Environmental Aspects of Dismantling of Old Buildings During the Reconstruction in Moscow. *19th International Multidisciplinary Scientific Geoconference SGEM 2019*. 2019;19:115–122. https://doi.org/10.5593/sgem2019/6.2/S26.015

About the Authors:

Lyubov I. Kastornykh, Cand.Sci.(Eng.), Associate Professor of the Department of Technological Engineering and Expertise in the Construction Industry at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ScopusID, ORCID, likas9@mail.ru

Alexander V. Kaklyugin, Sci. (Eng.), Associate Professor of the Department of Building Materials of the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation) ScopusID, ORCID, kaklugin@gmail.com

Mikhail G. Kholodnyak, Sci. (Eng.), Associate Professor of the Department of Technological Engineering and Expertise in the Construction Industry at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ORCID, xolodniak@yandex.ru

Denis V. Kuzmenko, Master's student of the Department of Technological Engineering and Expertise in the Construction Industry at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ORCID, 89001270357@mail.ru

Claimed contributorship:

LI Kastornykh: development of a plan and conducting research.

AV Kaklyugin: processing of experimental data.

MG Kholodnyak: processing of experimental data.

DV Kuzmenko: conducting experiments, preparing illustrations.

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

All authors have read and approved the final manuscript.

Об авторах:

Любовь Ивановна Касторных, кандидат технических наук, доцент кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, ORCID, likas9@mail.ru

Александр Викторович Каклюгин, кандидат технических наук, доцент кафедры строительных материалов Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, ORCID, kaklugin@gmail.com

Михаил Геннадиевич Холодняк, кандидат технических наук, доцент кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону , пл. Гагарина, 1), ORCID, xolodniak@yandex.ru

Денис Викторович Кузьменко, магистрант кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону , пл. Гагарина, 1), ORCID, 89001270357@mail.ru

Заявленный вклад авторов:

Л.И. Касторных: разработка плана и проведение исследовательских работ.

А.В. Каклюгин: обработка экспериментальных данных.

М.Г. Холодняк: обработка экспериментальных данных.

Д.В. Кузьменко: проведение экспериментов, подготовка иллюстраций.

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

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 30.04.2025
Reviewed / Поступила после рецензирования 17.05.2025
Accepted / Принята к публикации 30.05.2025

BUILDING MATERIALS AND PRODUCTS

СТРОИТЕЛЬНЫЕ МАТЕРИАЛЫ И ИЗДЕЛИЯ

Check for updates

Original Empirical Research

UDC 691.328
https://doi.org/10.23947/2949-1835-2025-4-2-67-74

EDN: JHDNVD

Method for Assessing the Density of a Concrete Mix during Molding

Spartak V. Edilyan ✉, **Khungianos S. Yavruyan**
Don State Technical University, Rostov-on-Don, Russian Federation
✉Spartak-edilyan@yandex.ru

Abstract.
Introduction. Concrete mix compaction is one of the most pressing topics in modern construction. Vibration compaction is a key method used to ensure uniform distribution of concrete mix components and removal of air voids.
The process of manufacturing reinforced concrete products is complex and labor-intensive and requires significant responsibility and attention. The quality of compaction of mixtures affects the physical and mechanical properties of molded products, including strength, water resistance, frost resistance and other important parameters. A correctly compacted mix ensures uniformity of properties of finished products, accuracy of geometric shapes and good quality of its front surface. The aim of this article is to study the existing works of the authors and identify the development area in the method of assessing the density of concrete mixture during molding with the possible development of the device necessary for this.
Materials and methods. Concrete mix was chosen as the object of the study. Control of concrete vibration compaction parameters requires careful planning, taking into account the type of mix, the shape of the structure and quality requirements. This section covers the development of a fundamentally new device "Shar-1".
Research results. The results of the development of a device for measuring the density of concrete mixture have been successfully proved experimentally. The device makes it possible to evaluate the compaction of the mixture during the forming process, recording data in real time and allowing further analyses of the concrete mixture compaction process. This helps to improve the quality control of concrete mixtures at the stage of moulding, which is important for improving the reliability and durability of concrete structures. The use of "Shar-1" simplifies and speeds up the testing process, reducing the influence of subjective factors and increasing the objectivity of measurements.
Discussion and Conclusion. The section focuses on the difference between traditional research on control of concrete mixture compaction and with the use of the device "Shar-1", which allows to measure the density of concrete mixture in the process of moulding. The method allows to quickly obtain data on density, timely correct the technology if necessary. It is planned to improve the device with additional functions in the future.

Key words: concrete, reinforced concrete, concrete mixture, compaction, vibration compaction, vibration platform, vibrations

For citation. Edilyan SV, Yavruyan HS. Method for Assessing the Density of a Concrete Mix during Molding. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):67–74. https://doi.org/10.23947/2949-1835-2025-4-2-67-74

Оригинальное эмпирическое исследование

Метод оценки плотности бетонной смеси в процессе формования

С.В. Эдилян ✉, **Х.С. Явруян**

Донской государственный технический университет, Ростов-на-Дону, Российская Федерация

✉ spartak-edilyan@yandex.ru

Аннотация.

Введение. Уплотнение бетонных смесей является одной из наиболее актуальных тем современного строительства. Вибрационное уплотнение — это один из основных методов, используемых для обеспечения равномерного распределения компонентов бетонной смеси и удаления воздушных пустот. Этот процесс позволяет достичь более высокой плотности и прочности бетона, что, в свою очередь, улучшает его эксплуатационные характеристики. Процесс производства железобетонных изделий представляет собой сложный и трудоёмкий, требующий значительной ответственности и внимания, процесс. Качество уплотнения смесей влияет на физико-механические свойства формуемых изделий, включая прочность, водонепроницаемость, морозостойкость и другие важные параметры. Верно уплотненная смесь обеспечивает однотипность свойств готовой продукции, точность геометрических форм и хорошее качество его лицевой поверхности. Целью данной статьи является описание работы принципиально нового оборудования «Шар-1», направленного на совершенствование методов оценки плотности бетонной смеси непосредственно в процессе формованию.

Материалы и методы. В качестве объекта исследования была выбрана бетонная смесь. Управление параметрами вибрационного уплотнения бетона требует тщательного планирования с учётом типа смеси, формы конструкции и требований к качеству. Исследование выполнялось с применением принципиально нового прибора «Шар-1».

Результаты исследования. Результаты разработки устройства для измерения плотности бетонной смеси успешно доказаны экспериментальным путем. Прибор позволяет оценивать уплотнение смеси в процессе формования, фиксируя данные в реальном времени и позволяя в дальнейшем анализировать процесс уплотнения бетонной смеси. Это способствует улучшению контроля качества бетонных смесей на стадии формования, что важно для повышения надежности и долговечности бетонных конструкций. Использование прибора «Шар-1» упрощает и ускоряет процесс испытаний, снижая влияние субъективных факторов и повышая объективность измерений.

Обсуждение и заключение. Раздел акцентируется на различии традиционных исследований по контролю уплотнения бетонной смеси и с применением прибора «Шар-1», который позволяет измерить плотность бетонной смеси в процессе формования. Метод позволяет быстро получать данные о плотности, своевременно корректировать технологию при необходимости. В дальнейшем планируется усовершенствовать прибор дополнительными функциями.

Ключевые слова: бетон, железобетон, бетонная смесь, уплотнение, виброуплотнение, виброплощадка, колебания

Для цитирования. Эдилян С.В., Явруян Х.С. Метод оценки плотности бетонной смеси в процессе формования. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):67–74. https://doi.org/10.23947/2949-1835-2025-4-2-67-74

Introduction. Vibration started being used for compacting concrete mixtures using pneumatic and ratchet vibration devices in 1890. There had been no new scientific data on the topic until 1915. In 1915, studies of vibro-compacted concrete and hand-made masonry accompanied with their comparative evaluation got underway causing new publications for comparative analysis to emerge. The effectiveness of vibration forming of concrete products depends on whether vibration modes and equipment parameters are chosen wisely. Telichenko V.I. and Vasiliev V.G. described a vibrating table, which is a movable platform on spring-loaded supports with two vibrators creating directional vibrations transmitted to the form and mixture [1].

However, lots of traditional concrete compaction methods might fail to provide the required quality, particularly while working with rigid concrete mixtures, since these are most often either destructive or insufficiently fast, which restrains their use in mass production. It is to be noted that the quality of concrete directly depends on the degree of its compaction, since this impacts the strength, durability and operational characteristics of structures.

In order to create strong and reliable concrete, it is critical to compact a concrete mix properly. This can be done by using vibration, a movement that assists concrete particles in fitting tightly together.

Vibrating setups have a major role to play in compacting concrete mixtures, ensuring the removal of air and voids from the mass of concrete, which causes a considerable increase in its strength and durability. If a mixture is sufficiently liquid, even a slight vibration, for example, might be sufficient due to its own weight. For thicker mixtures, more powerful vibration and, possibly, additional pressure are needed. Methods for optimizing the parameters of vibration setups, such as the frequency and amplitude of vibrations, to maximize the efficiency of machines, as well as the analysis and improvement of designs of electric vibration machines with a longitudinal gap of a magnetic core were elaborated on in [2].

If a mixture is sufficiently liquid, even a slight vibration, for example, might be sufficient due to its own weight. For thicker mixtures, more powerful vibration is needed. Owing to modern research, it is known that only 20–30 seconds is enough for the initial compaction of concrete. During this time, the concrete particles are redistributed by gravity, forming a solid and stable structure. As a result, the air is removed from a mixture, and eventually is not over 3–4% [3].

In the next stage, only a small combination of components is performed as some of the air is removed. The duration of the second stage of technological conversion is longer than that of the first one and is 2–3 minutes on standard vibrating pads. The end of the second stage is based on that of compaction of a concrete mixture. Once it is over, the freshly laid concrete can be considered ready to be processed further, as additional vibration causes no significant increase in the density, strength or quality of its surface [4].

Vibration plays a major role in forming concrete, but its efficiency depends on a whole host of factors. Although the vibration intensity might decrease as he source is moved away from due to the material properties and internal friction, this opens up avenues for optimizing the process [5, 6].

The quality and strength of concrete directly depend on a proper technology of laying and compacting a concrete mix, as these affect the uniformity of the material structure. By understanding how vibration waves propagate and interact in a concrete mix, one is able to develop more effective compaction methods. Although vibration attenuation at a distance from the source is a natural phenomenon caused by material properties and internal friction, it is not something impossible to deal with. All of this would enable us to achieve a uniform concrete structure even in complex shaped products. Research in this area is ongoing and we are sure that in the future the quality and efficiency of concrete products production will be increased further [7–9].

Investigating the interaction of vibration with reflected waves and natural vibrations of concrete will allow one to create optimal conditions for compaction even in complexly shaped products. The development of new vibration control methods paves the way to increased production efficiency as well as life cycle of equipment, and creation of high-quality concrete products [10].

Along with the modernization of equipment, scholars are working hard on a new method for assessing the quality of a concrete mix which relies on its ability to resist delamination. This method makes use of a special coefficient that shows how effectively cement is distributed in concrete. It is assumed that in a high-quality concrete mix, where all the components are evenly mixed, water will wash out more cement with a slow flow than with a fast one. This will allow one to quickly and precisely identify the quality of concrete and guarantee its strength and durability [11].

During the vibrational compaction of a concrete mixture, there are some mechanical effects leading to the permanent destruction of the bonds between its constituent particles. This, in turn, helps to reduce the forces of friction and adhesion. Due to its special consistency, a concrete mix is evenly distributed under the influence of gravity resulting in a homogeneous mass. In order to obtain the ultimate strength and durability of reinforced concrete products made from heavy mixtures, high density must be attained. Scientists are striving to ensure that the actual density of concrete is almost perfect. This is determined by the compaction coefficient, which should be at least 0.98, and preferably closer to a unit. This method ensures the reliability and durability of reinforced concrete products [12].

For a long time, the effectiveness of concrete vibration compaction was believed to reach its maximum when the particles of the concrete mixture are resonantly coupled to the vibration source. However, each fraction of the filler has its own unique oscillation frequency. This implies that the optimal sealing effect can be attained via a multi-frequency effect bringing all of the particles of a mixture into resonance. Self-synchronization is actually observed in a concrete mixture due to the binding effect of the cement paste uniting the individual grains of the aggregate. Therefore the efficiency of vibration compaction can be increased by optimizing the operating mode of the vibrator, which helps to synchronize the natural vibrations of the entire volume of a concrete mixture with the frequency of its operation [13].

The oscillation frequency determines the speed of movement of the particles of a concrete mixture. Changing the frequency allows the speed and intensity of compaction to be controlled. For example, for denser concrete mixtures, a higher oscillation frequency can be applied [14, 15].

Over the recent years, there has been a growing interest in optimizing vibration sealing parameters for increasing production efficiency and reducing costs. There is thus a need for system analysis and control of vibration parameters (frequency, amplitude, duration and exposure modes). In the future, this quality control method can be achieved by means of developing an effective and accurate method for estimating the density of a concrete mixture directly during molding improving the product quality and optimizing the production costs. This article looks at the main approaches to measuring the compaction of concrete mixtures experimentally using the "Shar-1" device developed by the authors.

Materials and Methods. The control of vibration seal parameters calls for careful planning and control. It is necessary to consider the type of a concrete mix, size and shape of the structure, as well as the requirements for the quality of concrete. The use of a variety of methods and approaches makes it possible to attain the optimal results and ensure the durability of concrete structures [16].

Vibration duration describes that of compaction. Time optimization makes it possible to achieve an even distribution of a concrete mixture and eliminate voids and irregularities. An exposure to vibration which is excessively long might cause the concrete mixture to separate, therefore a balance might be struck. Fig. 1 clearly shows the effect of the duration of compaction on the strength of concrete. The strength does not increase over a short-term and long-term compaction time, i.e., it is necessary to identify a point in time when the maximum compaction is recorded.

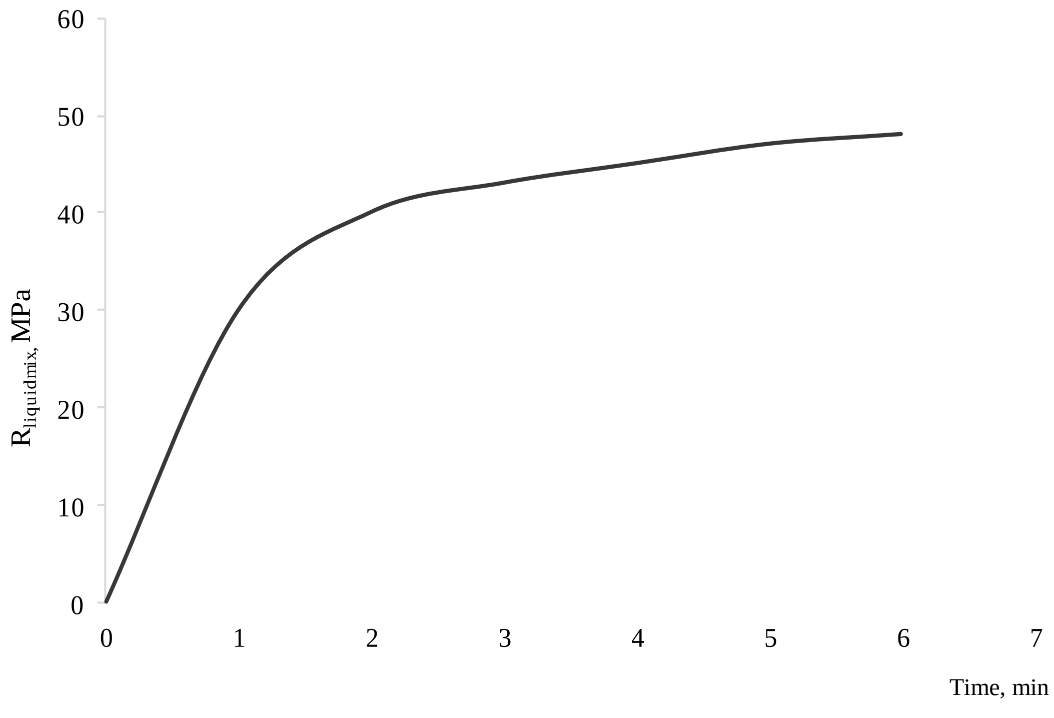


Fig. 1. Effect of the duration of compaction on the strength of concrete

To understand the processes occurring in the concrete mixture during its compaction, we have developed a fundamentally new device "Shar-1" (Fig. 2, 3).

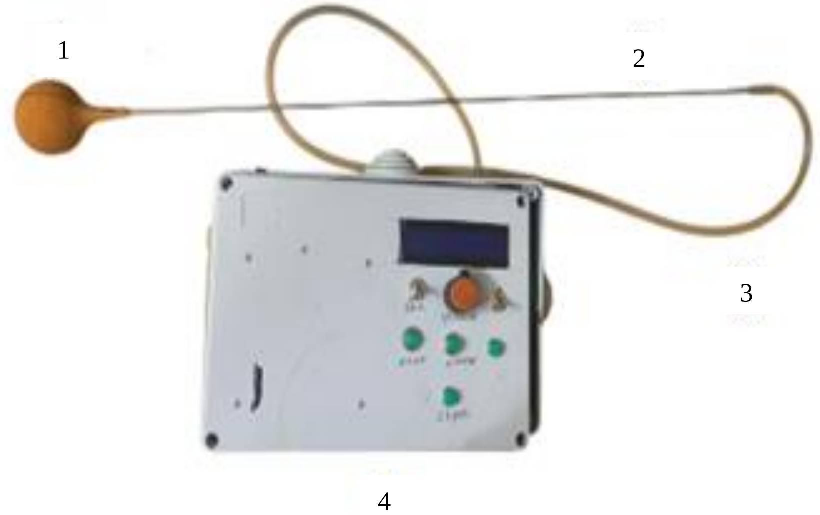


Fig. 2. Main parts of the "Shar-1" device: 1 — rubber ball; 2 — metal tube; 3 — rubber tube; 4 — control panel

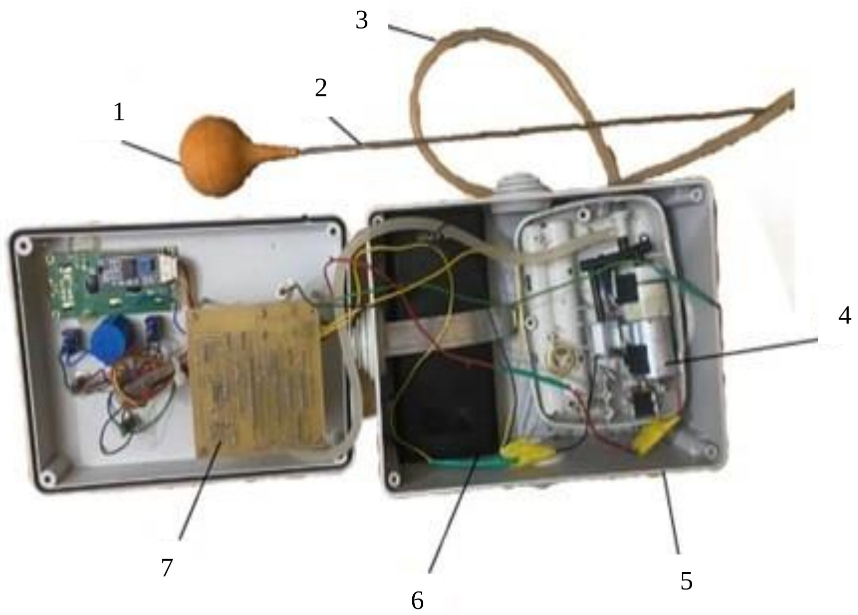


Fig. 3. Internal components of the “Shar-1” device: 1 — rubber ball; 2 — metal tube; 3 — rubber tube; 4 — control panel; 5 — body; 6 — battery, 7 — power board

The main working body of the device is a rubber ball under pressure connected through a metal hollow tube and a rubber tube to a pump in the control panel. Inside the rubber ball are a pressure sensor; a real-time clock; a vibration sensor measuring amplitude and vibrations. The case contains an SD drive for recording parameters on a power board; a battery for autonomous operation; a pump generating pressure in the ball for testing.

The pressure ball is at half the height of the metal mold, and this is when the process of compaction of a concrete mixture gets underway. Based on the physics of concrete compaction, it is known that during vibrations large particles tend to go down, and small ones go up respectively, which is called stratification. A ball under a certain pressure of 100 units placed in a mold starts contracting due to the pressure of a large fraction of a concrete mixture and reaches its maximum value. The maximum value of the Shar-1 device is considered to be the one when there is an equilibrium during compaction of a concrete mixture in the system, i.e., there will be no stratification. If there is one, theindices will start declining rapidly, as there is no more the equilibrium in the system , and a large proportion of a concrete mixture will be at the bottom, and a small (cement dough) fraction will be at the top. This indicates that the density between the upper layer and the lower ones differs, i.e., aconcrete mixture has experienced stratification.

Research Results. The development of the new "Shar-1" device is aimed at identifying the optimal quantitative indicator reflecting the full degree of compaction of a concrete mix while maintaining its strength characteristics. In order to identify this indicator, the working body of the "Shar-1" device is installed in a mold with a concrete mixture sequentially intorduced. As compaction gets underway, the device identifies the pressure on the working body over time and records the maximum values indicating the peak value of compaction of a concrete mixture.

The graph in Fig. 4 shows what the point of maximum compaction of the concrete sweep looks like through the course of the experiments.

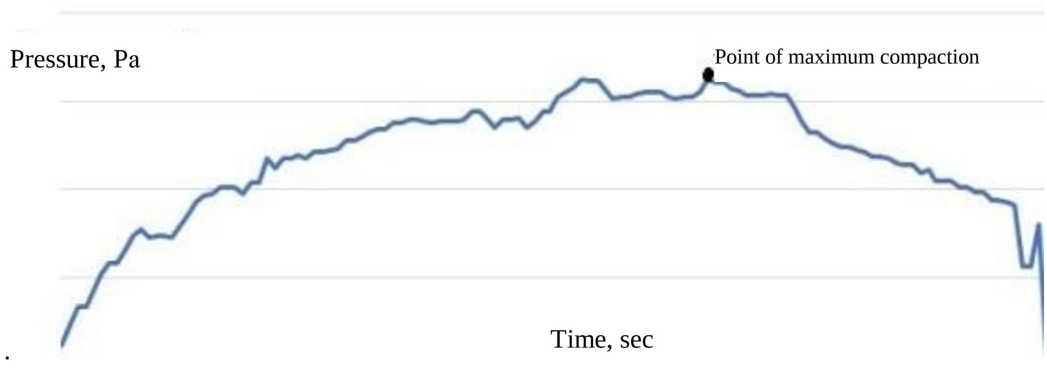


Fig. 4. Point of maximum compaction of a concrete mixture

The device is currently being tested and debugged. It is to be stressed that the use of devices capable of measuring the degree of compaction of a concrete mixture is currently restrained. However, the introduction of this method and the "Shar-1" device will be a breakthrough in concrete production technology with a positive impact on the economic growth of enterprises.

Discussion and Conclusion. Ensuring high-quality compaction of a concrete mix is an important step in construction, which is of paramount importance for the strength of future structures.

While working on the manuscript, we investigated the work of lots of authors and found a promising field of development, i.e., the development of a method for controlling the compaction of a concrete mixture during molding, which was the inspiration behind a completely new device "Shar-1". This method of density estimation using the developed device makes it possible to quickly obtain density data and allows for timely correction of compaction technology improving the quality and durability of concrete products, as well as reduces test time as well as the cost of preparation and measurement compared with traditional laboratory methods.

The mass use of this development in precast concrete production plants would involve an increase in the quality of products, a reduction in the human factor, and thereby in the likelihood of frequent errors as well as the production costs.

We are planning to refine the device to a more ergonomic appearance and as it is tested further, additional functions will be introduced to create an even more comprehensive and multifunctional device.

References

1. Edilyan SV, Yavruyan HS Analytical Review of Methods for Controlling the Parameters of Vibration Compaction of Concrete Mixes. *Modern Trends in Construction, Urban and Territorial Planning.* (In Russ.) 2024;3(3):15–21. https://doi.org/10.23947/2949-1835-2024-3-3-15-21

2. Dzhioev VK, Gobozov SF Analysis of Electrovibration Machines and Ways to Improve their Technical Performance. *Bulletin of the International Academy of Sciences, Ecology of Life Safety (MANEB).* 2010;15(2). (In Russ.)

3. Storozhuk NA, Dekhta TN Optimal Control of Concrete Mixtures Compacting by Vvibration Method and its Features.*Bulletin of PDABA.* 2018;4:243–243. (In Russ.) URL: https://cyberleninka.ru/article/n/optimalnoe-upravlenie-uplotneniem-betonnyh-smesey-vibratsionnym-sposobom-i-ego-osobennosti (accessed: 05.04.2025).

4. Yavruyan KhS, Lotoshnikova EO, Edilyan SV. Production technology of small products from fine-grained concrete. *Fundamental and Applied Scientific Research in the Development of Agriculture in the Far East (AFE-2022).* 2024;733:527–536. https://doi.org/10.1007/978-3-031-37978-9_51

5. Yavruyan HS, Lotoshnikova EO, Edilyan SV, Gaishun AS. Methodology for the selection of the composition for the production of products of hard-pressed concrete with industrial wastes. *Environmental risks and safety in mechanical engineering*. 2023;376:03025. https://doi.org/10.1051/e3sconf/202337603025

6. Edilyan SV, Yavruyan HS Review of Methods for Optimizing Vibration Compaction Modes of Concrete Mixtures. *Actual Problems of Science and Technology*. DSTU. 2023. 997–998 p. (In Russ.) URL: https://ntb.donstu.ru/conference2023 (accessed: 05.04.2025).

7. Garadzhaev A, Myradov Y, Ballyev G, Rakhymov B Placing and Compaction of Concrete Mixture. *Symbol of Science*. 2023;12(2):173–175. (In Russ.) URL: https://cyberleninka.ru/article/n/ukladka-i-uplotnenie-betonnoy-smesi (accessed: 05.04.2025).

8. Starodubtsev VG, Goryainov DA Study of the Influence of Concrete Mixture Laying and Compaction Technology on the Homogeneity of the Structure and Properties of Concrete. *Auditorium*. 2018. (In Russ.) URL: https://cyberleninka.ru/article/n/issledovanie-vliyaniya-tehnologii-ukladki-i-uplotneniya-betonnoy-smesi-na-odnorodnost-struktury-i-svoystv-betona (accessed: 05.04.2025)

9. Furmanov DV, Barulev AV, Tarasova NE, Chabutkin EK Dynamic Braking of Inertial Vibrators of Vibratory Platforms for Compaction of Concrete Mixtures. *Bulletin of the Siberian State Automobile and Highway Academy*. 2019;16(2):134–144. (In Russ.) https://doi.org/10.26518/2071-7296-2019-2-134-144

10. Burkhanov RKh Compaction of Rigid Concrete Mixture by a Working Element Performing Complex Spatial Movement. *Bulletin of the Saratov State Technical University*. 2013;2(71) (In Russ.) URL: https://cyberleninka.ru/article/n/uplotnenie-zhestkoy-betonnoy-smesi-rabochim-organom-sovershayuschim-slozhnoe-prostranstvennoe-dvizhenie

11. Merkulov SI Viability of Reinforced Concrete Structures and Structural Systems. *Construction and Reconstruction*. 2015;3:58–61. (In Russ.) URL: https://cyberleninka.ru/article/n/zhivuchest-zhelezobetonnyh-konstruktsiy-i-konstruktivnyh-sistem (accessed: 05.04.2025)

12. Telichenko VI, Vasiliev VG. Investigation of the spectrum of concrete mixture pulses at shock-vibration moulding. *Bulletin of V.G. Shukhov BSTU*. 2017;4:80–85. (In Russ.) URL: https://bulletinbstu.editorum.ru/ru/nauka/article/16036/view (accessed: 05.04.2025).

13. Gritsyuk TV *Influence of Molding Modes on the Surface Quality of Reinforced Concrete Products*. The Author's PhD in Engineering Disseration. Moscow; 1992. Pp. 9–20 p. (In Russ.) URL: https://elibrary.ru/zkpudb (accessed: 05.04.2025)

14. Dvorkin LI *Fundamentals of Concrete Science*. Saint Petersburg; 2006. 692 p.

15. Banfill PFG, Teixeira MAOM, Craik RJM. Rheology and Vibration of Fresh Concrete: Predicting the Radius of Action of Poker Vibrators from Wave Propagation. *Cement and Concrete Research*. 2011;41(9):932–941. https://doi.org/10.1016/j.cemconres.2011.04.011

16. Itkin AF. *Vibrating Machines for Molding Concrete Mixtures*. Kiev. MP "Lesya"; 2009. 152 p.

About the Authors:

Spartak V. Edilyan, PhD Student of the Technological Engineering and Expertise in the Construction Industry Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), ORCID, spartak-edilyan@yandex.ru

Khungianos S. Yavruyan, Cand.Sci. (Eng.), Associate Professor of the Technological Engineering and Expertise in the Construction Industry Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), ORCID, khungianos@mail.ru

Claimed Contributorship:

SV Edilyan: formulating the aim and objectives of the research, analysis of the research results, formulating the conclusions.

KhS Yavruyan: scientific supervision, formulating the main concept, refining the text, correcting the 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

Об авторах:

Спартак Варданович Эдилян, аспирант кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ORCID, spartak-edilyan@yandex.ru

Хунгианос Степанович Явруян, кандидат технических наук, доцент кафедры технологического инжиниринга и экспертизы в стройиндустрии Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), ORCID, khungianos@mail.ru

Заявленный вклад авторов:

С.В. Эдилян: формирование цели и задачи исследования, анализ результатов исследования, формирование выводов.

Х.С. Явруян: научное руководство, формирование основного концепции, доработка текста, корректировка выводов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 10.04.2025
Reviewed / Поступила после рецензирования 26.04.2025
Accepted / Принята к публикации 12.05.2025

LIFE CYCLE MANAGEMENT OF CONSTRUCTION FACILITIES
УПРАВЛЕНИЕ ЖИЗНЕННЫМ ЦИКЛОМ ОБЪЕКТОВ СТРОИТЕЛЬСТВА

Check for updates

Original Empirical Research

UDC 69.05
https://doi.org/10.23947/2949-1835-2025-4-2-75-84

Assessing the Benefits and Challenges of Implementing 4D Modeling in Construction

Konstantin M. Kryukov ✉
Don State Technical University, Rostov on Don, Russian Federation
✉ kkrioukov@gmail.com

EDN: DTRROH

Abstract

Introduction. Improved visualization is one of the results of the implementation of information modeling technology. Information modeling technology was mainly used by designers when developing a digital 3D model of an object. 4D modeling combines the organizational and technological sequence of works in the project with a parametric digital 3D model of the object under construction. 4D modeling can potentially contribute to the effective implementation of the project, but data on the scale of 4D implementation are limited, there is no empirical data in practice on the possibilities and problems of using this technology. The purpose of the study is to study the state of implementation of 4D modeling, the advantages of use, the main problems that hinder effective implementation, as well as incentives for implementation in the construction sector.

Materials and Methods. The article used a qualitative analysis of the functionality of 4D modeling to form a questionnaire for a survey among specialists in the construction industry. Based on the analysis of the array of data obtained, a statistical analysis was carried out to identify key problems and incentives for the implementation of 4D modeling in the activities of construction organizations.

Results. The main reasons for the insufficient implementation of 4D modeling technology in construction organizations are identified along with high awareness of the benefits of use. Critical problems that hinder the implementation of this technology are identified, as well as key factors that can stimulate the implementation of investment and construction projects using 4D modeling.

Discussion and Conclusion. The results of the study provide a basis for theoretical analysis to solve the problems of implementing 4D modeling in the construction industry. The study uses the theory of sustainable development and the theory of the full life cycle as a theoretical basis, combines qualitative and quantitative research methods, and conducts an in-depth study of various factors that affect the management of investment and construction projects using 4D modeling technology.

Keywords: 4D modeling; information modeling technology; implementation of BIM technologies

For citation. Kryukov KM Assessing the Benefits and Challenges of Implementing 4D Modeling in Construction. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):75–84. https://doi.org/10.23947/2949-1835-2025-4-2-75-84

Оригинальное эмпирическое исследование

Оценка преимуществ и проблем внедрения 4D-моделирования в строительство

К.М. Крюков ✉

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉ kkrioukov@gmail.com

Аннотация

Введение. Усовершенствованная визуализация — один из результатов внедрения технологии информационного моделирования. Технология информационного моделирования в основном использовалась проектировщиками при разработке цифровой 3D-модели объекта. 4D-моделирование объединяет организационно-технологическую последовательность работ в проекте с параметрической цифровой 3D-моделью строящегося объекта. 4D-моделирование потенциально может способствовать эффективной реализации проекта, но данные о масштабах внедрения 4D ограничены, в практической деятельности отсутствуют эмпирические данные о возможностях и проблемах использования данной технологии. Целью исследования является изучение состояния внедрения 4D-моделирования, преимуществ при использовании, основных проблем, мешающих эффективной реализации, а также стимулов для внедрения в строительном секторе.

Материалы и методы. В статье был использован качественный анализ функционала 4D-моделирования для формирования анкеты в целях опроса среди специалистов строительной отрасли. На основании анализа массива полученных данных проведен статистический анализ для выявления ключевых проблем и стимулов внедрения 4D-моделирования в деятельность строительных организаций.

На основании разработанной анкеты был проведен опрос среди заказчиков и подрядчиков строительной отрасли, которые были отобраны выборочным методом. Для анализа полученных данных использовались методы описательной статистики. Индекс относительной важности использовался для ранжирования показателей, чтобы понять относительную важность, как они воспринимаются респондентами. *T*-тест использовался для проверки статистической значимости предполагаемых различий между клиентами и подрядчиками. Коэффициент Альфа Кронбаха использовался для обеспечения внутренней согласованности и надежности данных для анализа.

Результаты исследования. Определены основные причины недостаточного внедрения в строительных организациях технологии 4D-моделирования наряду с высокой осведомленностью о преимуществах использования. Выделены критические проблемы, препятствующие реализации данной технологии, а также ключевые факторы, которые могут стимулировать реализацию инвестиционно-строительных проектов с применением 4D-моделирования.

Обсуждение и заключение. Результаты исследования обеспечивают основу теоретического анализа для решения проблем внедрения 4D-моделирования в строительной отрасли. Исследование использует теорию устойчивого развития и теорию полного жизненного цикла в качестве теоретической основы, сочетает в себе качественные и количественные методы исследования и проводит углубленное изучение различных факторов, которые влияют на управление инвестиционно-строительными проектами с использованием технологии 4D-моделирования.

Ключевые слова: 4D-моделирование, технология информационного моделирования, внедрение BIM технологий

Для цитирования. Крюков К.М. Оценка преимуществ и проблем внедрения 4D-моделирования в строительстве. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):75–84. https://doi.org/10.23947/2949-1835-2025-4-2-75-84

Introduction. Construction is an important industry in Russia’s economy and ranks 5th among the branches of the national economy according to its contribution to the gross domestic product. The industry is witnessing a rapid growth [1] (Fig. 1).

The level of complexity of investment and construction projects is extremely high due to customers’ increasing demands. Traditional project implementation systems are largely focused on project completion dates and costs. Unfortunately, under the current conditions, designers, contractors and manufacturers of building materials are not always capable of completing their tasks on time, within a set budget and cater for their customers’ needs. What is more, many fail to achieve the desired outcome [1].

Building information modeling provides participants in investment and construction activities with a platform for collaboration in a shared data environment for increasing the efficiency and improve the outcome. The 3D model of the project documentation can be used for construction planning. When the "time" parameter is added to the model, 4D

[1] The statistical data were accessed from https://rosstat.gov.ru/

modeling is implemented. 4D modeling enhances the efficiency of processes by reducing unproductive costs and helps to complete projects on time within a set budget controlling the construction schedule and increasing value for customers [2]. However, despite these opportunities, 4D modeling is not commonly used by construction project participants. It is thus proposed that the degree of use is assessed and the point of view of key construction actors on the advantages, obstacles and motivational forces of 4D modeling is understood.

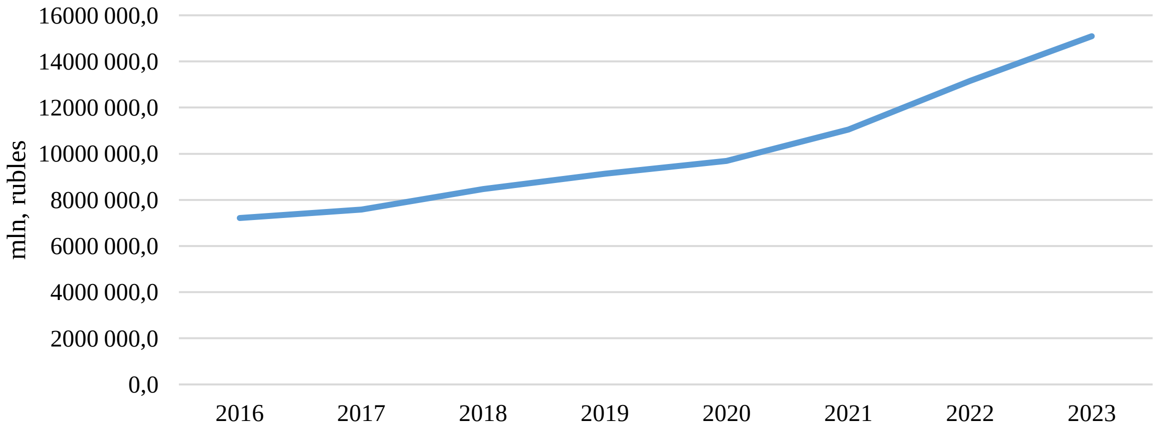


Fig. 1. Dynamics of the indicator "Amount of Work Performed Independently according to an activity type "Construction""

Traditional planning methods are not directly related to the design and construction model [3], the sections of the plans are not in complete synchrony with the project making it difficult for project participants to make sense of the plan and its impact on logistics management at the facility [4]. The lack of this connection causes alterations, unevenness and improper use of resources, which increases construction time and costs [5].

4D modeling is also instrumental in speeding up construction thus reducing the number of errors that are easily eliminated at the design stage, avoiding major problems that are rather expensive to resolve at a later stage of construction [6, 7].

4D modeling offers an expanded vision of planning, designing and building, developing or maintaining a single information model including all of the necessary information about the project lifecycle. 4D modeling plays a major role in the coordination between designers and customers during the planning phase. The experience of contractors is crucial while developing a 4D model for planning and is capable of providing valuable information about the feasibility of construction, the estimated construction costs and the sequence of work [4]. This helps project stakeholders to identify problems during the construction phase and keep track of work progress [2, 8]. 4D modeling helps to design virtual projects and stimulate them with various scenarios, which enables all stakeholders to gain a better insight into the risks of the project at an early stage and their reduction by taking corrective measures.

The major advantages and applicability of 4D modeling are visualization of the progress of construction at any time with possible forecasting [8, 9]; logistics planning (movement of resources on the construction site) [10]; site layout (reduces losses that might take place during construction, thus improving construction opportunities) [9, 11]; location-based planning [9]; a clear understanding of the construction process and construction methodology [9]; checking schedules using modeling [12]; discussing progress in meetings for a better insight [12]; safety planning (visual representation of hazards and a safety plan) [9, 11]; analysis of the documentation and claims (it is quite easy to prove which party is to be held accountable for the delay and what potential outcomes are to be expected) [12]; reducing risks in the project [9]; increasing customer satisfaction [10]; monitoring the project with modeling a schedule that helps to reduce the amount of necessary improvement [9].

Notwithstanding the advantages that 4D modeling offers to the construction industry, there are technical and non-technical problems preventing 4D modeling from being commonly adopted [8]. The widespread adoption of BIM and 4D modeling is more affected by non-technical barriers than technical ones. Information on the scale of 4D modeling implementation in Russia is rather limited. Hence the experience of using 4D modeling overseas where this method is most common was investigated. These countries are Great Britain, France, Slovakia, the USA, Iran, etc. Scholars and practitioners in all of these countries note the problems associated with the development of the 4D model (model volume, level of detail, time components, decomposition and aggregation) and the lack of proper implementation plans, guidelines and standards to be adhered for 4D modeling to be implemented. The inexpediency of spending time on training and the lack of time for employees' training is also noted. A major obstacle to implementation is the lack of 4D modeling experience in the market, the lack of standards for 4D modeling, difficulties in understanding the methods, and the longer process of creating a 4D model [9-13]. There is also insufficient customer demand for the use of the 4D model, high software investment as well as training costs, lack of knowledge of 4D modeling among the workforce, employees' resistance to abandoning traditional construction planning methods and switching to 4D modeling, as well as problems with data exchange between software related to software compatibility.

The construction industry has become somewhat aware of the value of BIM and started using it during the design phase, but the use of BIM during the planning and construction phases is growing at a slow rate. There have been no studies on the implementation of 4D modeling in Russia. There is thus a need to investigate the status of 4D modeling implementation in Russia as well as the perceived advantages and issues of various subjects of investment and construction activities in the construction sector. The aim of the study is to investigate the extent of the use of 4D modeling, the views of the main stakeholders on 4D modeling when it comes to the advantages, obstacles and motivational forces in the Russian construction.

Materials and Methods. The target audience of the study is customers and contractors of the construction industry. A sampling method was employed in order to select the respondents. In order to conduct the survey, a questionnaire was designed including information about the demographic data of the participants, as well as some questions on the applicability of 4D modeling, the advantages of 4D models as opposed to traditional approaches to construction planning, the challenges of implementing 4D modeling, and motivational efforts to implement 4D modeling.

Descriptive statistics methods were used in order to analyze the data. The relative humidity index is employed in order to rank the indicators for a better insight into the relative importance of how they are seen by the respondents. The T-test is used to verify the statistical significance of the perceived differences between the clients and contractors, if any. The Cronbach Alpha coefficient is used to ensure the internal consistency and reliability of the data for analysis.

The survey tool was designed digitally and requests were sent to customers-developers and contractors of the Southern Federal District by e-mail. 27 responses were received, including from 17 contractors and 10 from construction customers. Cronbach's Alpha is used to evaluate the internal consistency of the instrument and the reliability of the data collected for further analysis. The calculated values of Cronbach's Alpha are made in Excel and shown in Table 1. All the values are over 0.7 (the threshold for social research) making the data collected reliable and acceptable for further analysis.

Table 1

Reliability statistics

Name	Cronbach's Alpha	Number of the indicators
Possibility of use	0.906	12
ПAdvantages	0.925	12
Issues	0.812	14
Incentives for use	0.835	6
Total	0.894	44

Research Results. Information modeling technology functions are used to assess the feasibility of applying the advantages, obstacles, and driving forces of 4D modeling. According to the study of the used sources, indicators were designed that are to be further investigated (Table 2).

A quantitative approach based on a survey is used to examine construction professionals' views on applicability, advantages, obstacles and driving forces of using 4D modeling in implementing investment and construction projects.

There were 27 responses received, with most provided by large organizations (71.8%), whereas the remainde were medium-sized (10.8%) and small (17.4%) organizations. The respondents are the top management (23.9%), middle management (54.8%) and operational (21.3%) levels in their organizations. The respondents' work experience in construction is as follows: 35% have more than a 10- year work experience, 36% of the respondents have a 5–10 year work experience, 19% of the respondents have a 2–5 year work experience, and 10% of the respondents have less than a 2–year work experience.

Knowledge and use of 4D modeling. It was noted that most (74%) of the respondents know about 4D modeling, but have not used it, whereas 11% both know and use it, and 15% said that they did not know about 4D modeling (Fig. 2). Some of the respondents use the concept of 4D BIM, which is essentially equivalent to the concept of 4D modeling.

Table 2

BIM functions, challenges, and incentives for using 4D modeling

№ of the indicator	Name of the indicator
1. Functionality implemented during the introduction of 4D modeling	
1.1	Logistics planning
1.2	Planning the organization of the construction area
1.3	Interconnection of individual construction plans of the contractors involved in construction
1.4	Planning of the organizational and technological sequence of work
1.5	Construction process visualization
1.6	Planning accounting for the location
1.7	Checking the construction plan using modeling
1.8	Possible work meetings held during the construction
1.9	Safety planning
1.10	Documenting and analyzing claims
1.11	Risk management
1.12	Variant design with construction schedule modeling
2. Issues of introducing 4D-modeling	
2.1	Lack of customer demand for using the 4D model
2.2	High software investment costs
2.3	High training costs
2.4	Employees' insufficient knowledge of 4D-modeling
2.5	No experience of 4D-modeling in the market
2.6	Unnecessary time spent on training
2.7	Insufficient time for the employees' training
2.8	Employees' resistance to change
2.9	No 4D-modeling standards
2.10	Issues of developing the 4D-model
2.11	Challenges of understanding the 4D-modeling methods
2.12	Traditional methods of implementing the project/contract
2.13	A more lengthy process of designing 4D-modeling
2.14	Issues of data exchange between the software programs
3. Incentives for implementing 4D-modeling	
3.1	Developing local 4D-modeling standards
3.2	State support of 4D-modeling
3.3	Improving the software functionality
3.4	Software providers' support
3.5	Knowledge of the advantages of 4D-modeling and return on investment
3.6	Positive examples of the use of 4D-modeling in the market

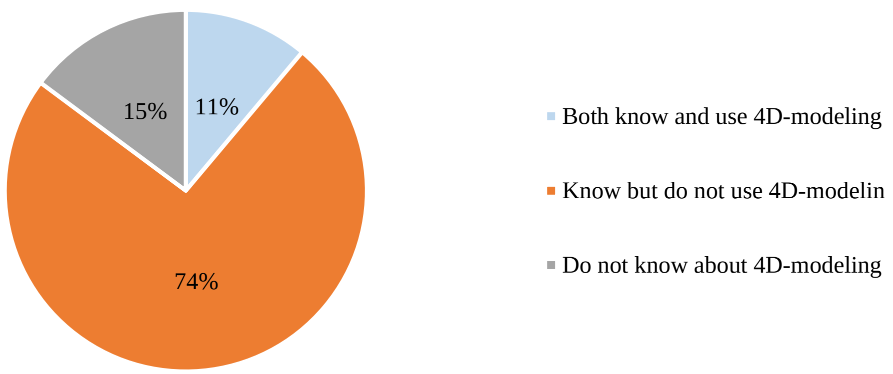


Fig. 2. Knowledge and use of 4D-modeling

The results indicate a higher level of awareness about 4D modeling and a much lower level of use. An attempt was made to make sense of the plan of the respondents who know about but did not use 4D modeling. Although some of the respondents indicated that they were planning to use 4D modeling in the foreseeable future (11% within a year and 31% within 1–3 years), a significant proportion (58%) of the respondents are planning to use 4D BIM only after 3 years (Fig. 3). This implies an expected lower spread of 4D BIM in the short term.

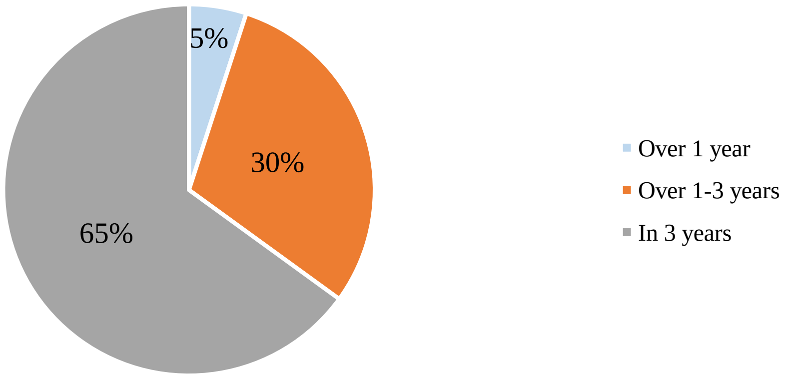


Fig. 3. Plans to implement 4D-modeling

Applicability of 4D BIM. The participants were asked to express their opinion on the possibility of using 4D modeling functionality on a five-point Likert scale (from "not applicable at all" to "very applicable") in relation to the various BIM functions according to the list provided in Table 2. The distribution of the responses is shown in Fig. 4. Their structure indicates that the respondents rated 4D modeling as applicable. Among the BIM functions, "Visualization of the Construction Process" (1.5), "Interconnection of Individual Construction Plans of Contractors Involved in Construction" (1.3) and "Verification of the Construction Plan Using Modeling" (1.7) turned out to be the most preferred ones. Although "Planning of the Construction Site Organization" (1.2) and "Logistics Planning" (1.1) were ranked low, they can be considered applicable. On top of that, the clients rated "Variant Design with Construction Schedule Modeling" (1.12) as very applicable.

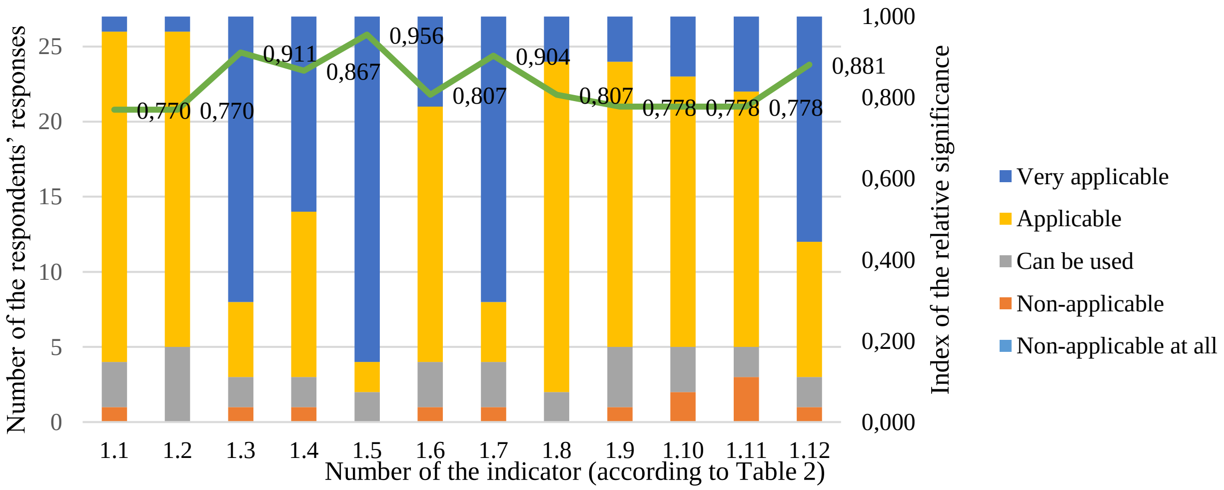


Fig. 4. Possibility of using the 4D-modeling functional

Advantages of using 4D modeling. In response to a question about the advantages and usefulness of 4D modeling, participants rated the various BIM functions listed in Table 2 on a five-point Likert scale (from "not profitable at all" to "very profitable"). The distribution of the responses is shown in Fig. 5.

It can be noted that the response pattern is similar to the one shown above (Fig. 4). "Visualization of the construction process" (1.5), "Interconnection of individual construction plans of contractors involved in construction" (1.3) and "Verification of the construction plan using modeling" (1.7) were evaluated as the main advantages of 4D modeling. However, respondents believe that "Variant design with modeling of the construction schedule" (1.12) is more useful than "Interconnecting individual construction plans of contractors" (1.3). It should be noted that high scores on other indicators indicate the very beneficial nature of 4D modeling.

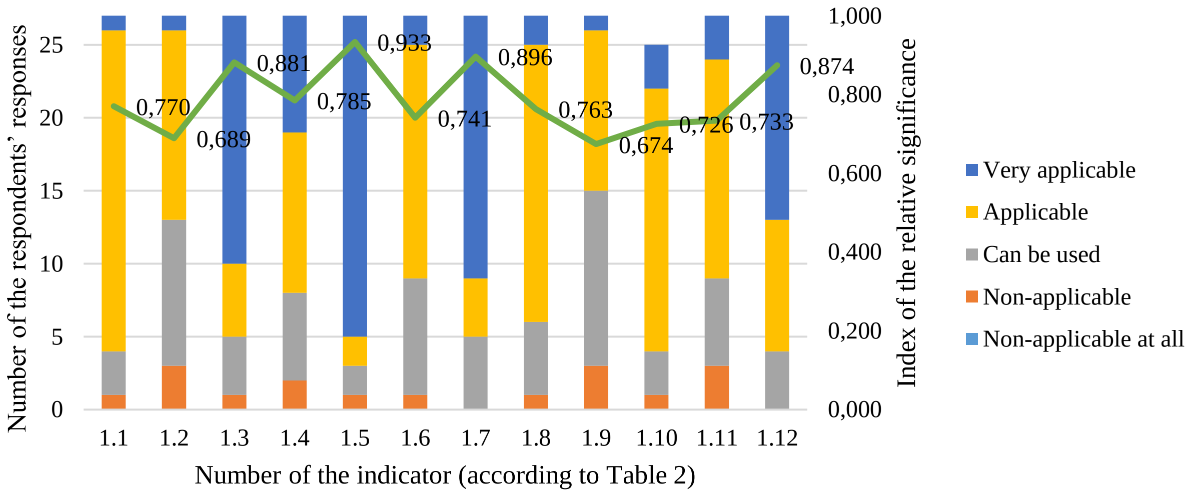
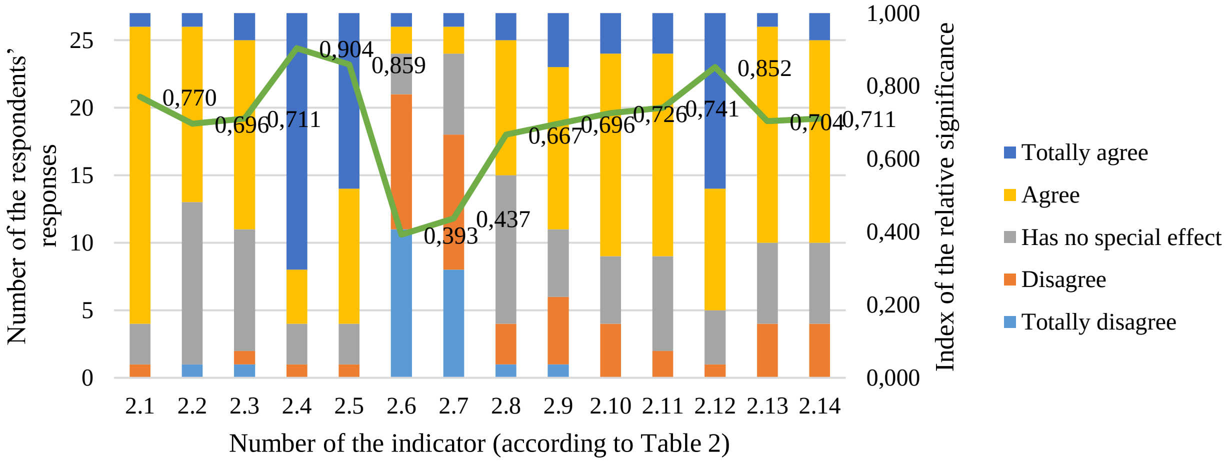


Fig. 5. Advantages of using 4D-modeling

Issues of 4D modeling implementation. The respondents believe that "Lack of knowledge of 4D modeling among employees" (2.4), "Traditional methods of project/contract implementation" (2.12) and "Lack of 4D modeling experience in the market" (2.5) are the major obstacles to the introduction and use of 4D modeling (Fig. 6). "Unjustified costs time for training" (2.6) and "Lack of time for employee training" (2.7) were assessed as minor issues for implementation.



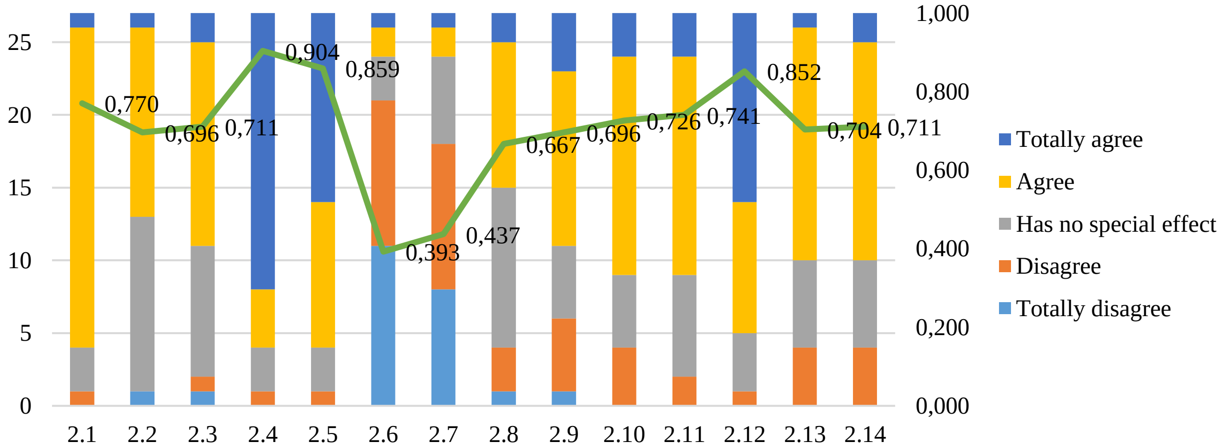
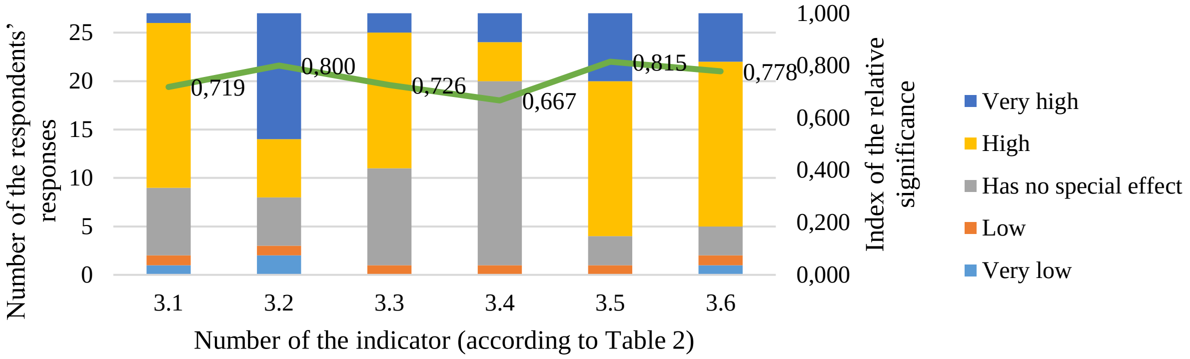


Fig. 6. issues of implementing 4D-modeling

Incentives for using 4D modeling. In response to a question about the driving forces contributing to the implementation of 4D modeling in organizations, on a five-point Likert scale (from "very low" to "very high"), the respondents rated "Knowledge of the benefits of 4D modeling and return on investment" (3.5) as the major criterion (Fig. 7).



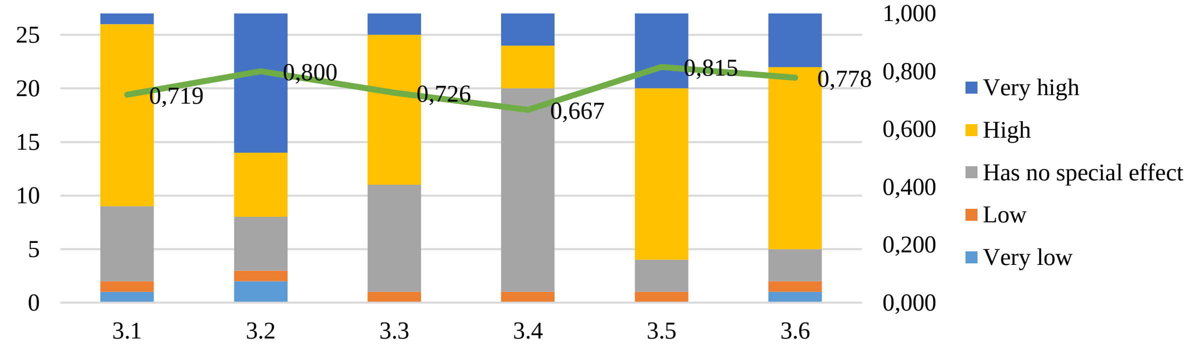


Fig. 7. Incentives for using 4D-modeling

Along with 3.5, "Government support" (3.2) and "Accessibility of 4D modeling experience in the market" (3.6) are also considered as the major factors. It can be noted that "Support from software vendors" (3.4) was ranked the lowest.

Hypothesis testing. Although there was generally agreement among the construction customers and contractors on their responses, an attempt was made to test that statistically to ensure that this was not by chance. The independent *t*-test is a statistical test that is used to identify the difference in averages.1 In addition, the t-test is applicable when only two groups are compared, and the sample size is very small. The following hypotheses are tested using the t-test for two independent samples assuming equal variance at a significance level of 5%.

Null hypothesis H_0: There is no significant difference in the perception by the customers and contractors of the applicability, advantages, challenges, and incentives of implementing 4D modeling.

Alternative Hypothesis H_1: To test the null hypothesis, there is a significant difference in the perception of the customers and contractors regarding the applicability, benefits, challenges, and incentives of implementing 4D modeling in the construction industry.

The test results are shown in Table 3. The p-value indicator was used to verify the test results, which indicates the probability of obtaining the observed results if the null hypothesis is correct, or the probability of error if the null hypothesis is rejected. As the p-value for all of the four variables is over 0.05, there is no sufficient evidence to reject H_0, and H_0 is thus accepted. This means that there is no significant difference in the perception by the customers and contractors of the applicability, advantages, challenges, and incentives of implementing 4D modeling.

Table 3

Results of the *t*-criterion for the null hypothesis

Variables	*p*-value
Applicability	0.134
Advantages	0.707
Issues	0.367
Incentives	0.132

Discussion and Conclusion. According to the study, it can be noted that there is a high level of knowledge knabout 4D modeling in construction. However, the task is to turn this knowledge into practice. Despite the increased knowledge and willingness to use 4D models, most of the respondents do not plan to use this information modeling technology in the next three years. In order to be competitive in the market and successfully implement investment and construction projects on time, with proper quality and within a set budget, there is a significant need to implement 4D modeling in construction organizations as early as possible.

Reviews of the applicability and advantages of 4D modeling (1.5, 1.3, 1.7 and 1.12 of Table 2) emphasize the need for improved visualization for communication between the general contractor and subcontractors for timely transfer of the work, the possibility of preliminary organizational and technological modeling of a range of options for managing the construction process in order to complete the project on time as stipulated by the contract. Building capacity and opportunities through education and training is critical to meeting these expectations. Construction customers can predict various project implementation options with the modeling of the construction plan (1.12), which demonstrates a change in priority towards project quality and timely logistics.

It is also important to pay attention to the obstacles to the implementation of 4D modeling. "Lack of knowledge about 4D modeling tools among the employees of construction organizations" (2.4) calls for special attention to training and continuous professional development within organizations. In order to address these issues, it is necessary to change the "Traditional approach to project implementation" (2.12), apply innovative procurement methods such as integrated project implementation (IPD) and smart contracts using blockchain. "Lack of experience using 4D modeling in the market" (2.5) calls for educational institutions to review curricula to ensure that students graduate with the necessary digital skills. As "Unjustified time spent on training" (2.6) and "Lack of time for employees' training" (2.7) were assessed as minor issues, meaning that organizations and their employees are willing to accept these changes and implement modern modeling approaches.

While focusing on the incentives for using 4D modeling, it can be noted that it is necessary to promote information about the advantages of implementing 4D modeling, to prove the efficiency of investing in this stage of information modeling technology (3.5). Therefore "Government support for the use of 4D modeling" (3.2) plays a key role through the development of appropriate standards, training programs, and other incentive measures. Currently, there is no official set of rules reflecting approaches to the use of 4D modeling. It is only SP 331.1325800.2017 "Information Modeling in construction" that gives a definition of 4D.

It can be noted that the major advantages of using 4D modeling are found in studies conducted overseas. Certainly, there are a few differences. E.g., in the UK [8], "Logistics planning" (1.1) was ranked high, and the lack of knowledge of the project participants was attributed to crucial problems. The unavailability of qualified specialists has proved to be a critical factor in Qatar's construction industry. In India, the use of existing project implementation methods and lack of customer demand were identified as the major challenges facing 4D modeling.

Considering the relatively small sample size, the conclusions are to be trusted with some reservations. A wider study among customers and contractors with an increased sample size might shed more light. It is also worth exploring the role of visualization for communication in decision-making by all project participants in order to improve implementation of investment and construction projects.

References

1. Stolbov IV Modern Approaches to the Integrated Implementation of Information Modeling Technologies at all Stages of the Life Cycle of a Capital Construction object /Real Estate Object. *Science Prospects.* 2023;165(6):108–113 (In Russ.) URL: https://moofrnk.com/assets/files/journals/science-prospects/165/science-prospect-6(165)-main.pdf (accessed 10.04.2025)

2. Bovteev SV Current State and Prospects for the Usage of 4D Modeling in the Sphere of Construction in the Russian Federation. *Bulletin of Civil Engineers.* 2023;97(2):65–74. (In Russ.) http://doi.org/10.23968/1999-5571-2023-20-2-65-74

3. Wang L, Lee J, Nimawat Ja. Integrated 4D Design Change Management Model for Construction Projects. *Journal of Construction Engineering and Management - ASCE*. 2024;150(5). http://doi.org/10.1061/jcemd4.coeng-14246

4. Nechiporchuk Y, Bashkova R Brief Overview of 4Dmodeling in Construction. *Architecture. Construction. Education.* 2020;15(1):35–41. (In Russ.) http://doi.org/10.18503/2309-7434-2020-1(15)-35-41

5. Pimenov SI Levels of Decomposition of Construction Digital information models (4 D models) for the Tasks of Organizational and Technological Modeling of Construction Production. *News of Higher Educational Institutions. Construction.* 2023;770(2):65–78. (In Russ.) http://doi.org/10.32683/0536-1052-2023-770-2-65-78

6. Swallow M, Zulu S Benefits and Barriers to the Adoption of 4D Modeling for Site Health and Safety Management. *Front. Built Environ*. 2019;4:86. http://doi.org/10.3389/fbuil.2018.00086

7. Crowther J, Ajayi SO Impacts of 4D BIM on construction project performance. *International Journal of Construction Management*. 2021;21(7):724–737. http://doi.org/10.1080/15623599.2019.1580832

8. Doukari O, Seck B, Greenwood D. The efficient generation of 4D BIM construction schedules: A case study of the Nanterre 2 CESI project in France. *Frontiers in Built Environment.* 2022;8. http://doi.org/10.3389/fbuil.2022.998309

9. Shcherba NV, Kuzhin MF Optimization of Calendar and Resource Planning Using BIM Technologies in Industrial Construction. *Construction Production.* 2020;3:35–40. (In Russ.) http://doi.org/10.54950/26585340_2020_3_35

10. Gushchina YuV, Saushkin DA Optimization of construction calendar plans based on BIM modeling. Bulletin of the Volgograd State University of Architecture and Civil Engineering. Series: Construction and architecture. 2020;81(4):438–447. (In Russ.) URL: https://elibrary.ru/item.asp?id=44694133 (accessed: 10.04.2025).

11. Sharmanov VV, Romanovich MA, Simankina TL Management of the Construction Process Using a Digital Construction Organization Project. *Engineering Journal of Don.* 2024;111(3):678–695. (In Russ.) URL: https://cyberleninka.ru/article/n/upravlenie-protsessom-stroitelstva-s-pomoschyu-tsifrovogo-proekta-organizatsii-stroitelstva (accessed: 10.04.2025).

12. Biche-Ool HV Practical Application of 4D Modeling in Construction Organizations of the Republic of Tuva. *Bulletin of the Tuva State University.* No. 3 *Technical and Physical and Mathematical Sciences.* 2022;94(2):14–20. (In Russ.) http://doi.org/10.24411/2221-0458-2022-94-14-20

13. El-Habashy Sh, Alqahtani FK, Mekawy M Identification of 4D-BIM Barriers in Offshore Construction Projects Using Fuzzy Structural Equation Modeling. Buildings. 2023;13(6):1512. http://doi.org/10.3390/buildings13061512

About the Author:

Konstantin M. Kryukov, Cand. Sci. (Eng.), Associate Professor of the Department of Construction Management at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ScopusID, ORCID, kkrioukov@gmail.com

Conflict of interest statement: the author does not have any conflict of interest.

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

Об авторе:

Константин Михайлович Крюков, кандидат экономических наук, доцент кафедры организации строительства Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, ORCID, kkrioukov@gmail.com

Конфликт интересов: автор заявляет об отсутствии конфликта интересов.

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 12.04.2025
Reviewed / Поступила после рецензирования 02.05.2025
Accepted / Принята к публикации 13.05.2025

LIFE CYCLE MANAGEMENT OF CONSTRUCTION FACILITIES

УПРАВЛЕНИЕ ЖИЗНЕННЫМ ЦИКЛОМ ОБЪЕКТОВ СТРОИТЕЛЬСТВА

Check for updates

Original Empirical Research

UDC 69.001.5
https://doi.org/10.23947/2949-1835-2025-4-2-85-95

EDN: GCHTJX

Sustainable Development Paths for Urban Eco-Architecture

Zhang Haoran[1], Svetlana G. Sheina[2], Vladimir V. Belash[2] ✉
[1]Shandong Jiaotong University, Jinan, Shandong Province, China
[2]Don State Technical University, Rostov-on-Don, Russian Federation
✉ vbelash@donstu.ru

Abstract

Introduction. Environmental development issues have become acutely relevant of late. Therefore eco-architecture is taking centre stage. By using sustainable design concepts and eco-friendly materials, eco-architecture reduces dependence on natural resources, as well as energy consumption and waste emissions, thus effectively decreasing the burden on the environment. Hence not only is eco-architecture an essential area of sustainable urban development, but also provides one with a practical way of designing a more harmonious and high-quality living environment. The aim of the study is to identify the principles of eco-architecture and assess its impact on the sustainable development of the urban environment. The impact of eco-architecture on the entire construction cycle of buildings and structures from the moment of construction to the demolition of the building is examined, and the ways of sustainable development of urban architecture are identified.

Materials and Methods. Ways of sustainable development of eco-architecture in the modern world are analyzed. Various negative impacts such as air and water pollution, noise, landscape and ecosystem disturbance occur during the construction and opera-tion of buildings. To minimise these impacts, it is necessary to develop environmental protection measures and take environmental aspects into account at all stages of design and construction.

Research Results. The study assessed the sustainability of the development of eco-architecture according on the analysis of the life cycle of the building, accounting for the environmental impact at the stages of design, construction, use and demolition of the construction site.

Discussion and Conclusion. The sustainability assessment of eco-architecture is based on the analysis of the building's life cycle, accounting for the environmental impact at all the stages: from design and construction to use and demolition. A comprehensive analysis of the resource consumption and environmental load of the building at different stages would enable one to assess sustainability more accurately. As digital technologies are evolving, the use of intelligent buildings and the Internet of Things (IoT) will enable data to be monitored and analyzed in real time. This will improve the sustainability management of buildings during the operational phase by providing data support in order to optimize resource efficiency.

Keywords: eco-architecture, sustainable development, ecological energy efficiency, low carbon content, resource recycling, environmental friendliness, building lifecycle, urban development, environment

For citation. Zhang Haoran, Sheina SG, Belash VV Sustainable Development Paths for Urban Eco-Architecture. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):85–95. https://doi.org/10.23947/2949-1835-2025-4-2-85-95

Оригинальное эмпирическое исследование

Пути устойчивого развития для городской эко-архитектуры

Чжан Хаожань[1], С.Г. Шеина[2], В.В. Белаш[2] ✉

[1]Шаньдунский транспортный университет, г. Цзинань, провинция Шаньдун, Китайская народная республика

[2]Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉ vbelash@donstu.ru

Аннотация

Введение. В последнее время вопросы экологического развития стали особенно актуальны, поэтому важность эко-архитектуры выходит на первый план. Используя концепции устойчивого проектирования и экологичные материалы, эко-архитектура снижает зависимость от природных ресурсов, уменьшает потребление энергии и выбросы отходов, тем самым эффективно снижая нагрузку на окружающую среду. В связи с этим эко-архитектура является не только важным направлением устойчивого развития городов, но и предоставляет нам практический путь к созданию более гармоничной и качественной среды обитания. Целью данного исследования является определение принципов эко-архитектуры и оценка его влияния на устойчивое развитие городской среды. Проанализировано влияние эко-архитектуры на весь цикл строительства зданий и сооружений с момента строительства и до сноса здания, и определены пути устойчивого развития городской архитектуры.

Материалы и методы. Проведен анализ путей устойчивого развития эко-архитектуры в современном мире.

Результаты исследования. В ходе исследования выполнена оценка устойчивости развития эко-архитектуры на основе анализа жизненного цикла здания с учетом воздействия на окружающую среду на этапах проектирования, строительства, использования и сноса объекта строительства

Обсуждение и заключение. Оценка устойчивости развития эко-архитектуры основывается на анализе жизненного цикла здания, учитывая воздействие на окружающую среду на всех этапах: от проектирования и строительства до использования и сноса. Всесторонний анализ потребления ресурсов и экологической нагрузки здания на разных этапах позволит получить более точную оценку устойчивости. С развитием цифровых технологий применение интеллектуальных зданий и Интернета вещей (IoT) сделает возможным мониторинг и анализ данных в режиме реального времени. Это позволит улучшить управление устойчивостью развития зданий на этапе эксплуатации, обеспечив поддержку данных для оптимизации эффективности использования ресурсов.

Ключевые слова: эко-архитектура, устойчивое развитие, экологическая энергоэффективность, низкое содержание углерода, переработка ресурсов, экологичность, жизненный цикл здания, городское развитие, окружающая среда

Для цитирования. Чжан Хаожань, Шеина С.Г., Белаш В.В. Пути устойчивого развития для городской эко-архитектуры. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):85–95. https://doi.org/10.23947/2949-1835-2025-4-2-85-95

Introduction. As cities are sprawling, pre-existing natural habitats are being exploited on an unprecedented scale causing a dramatic reduction in biodiversity and puts lots of species under risk of extinction. Intensive urbanization affects the quality of life leading to air and water pollution, increased noise, reduced green space, high density of buildings and population. All of these did not only disrupt the balance of the ecosystem, but also posed a threat to the human environment as well as made it imperative to rethink the existing approaches to architectural and spatial organization of the urban environment [1]. A way to address these challenges is the concept of eco-architecture combining respect for nature and concern for human health and comfort. Ecological architecture dates back to the beginning of the last century to the theory of "renewable resource management" which considered the issues around replacing traditional energy sources with alternative ones. It suggested using solar electricity produced by spherical collectors [2]. Variants of solar installations have been developed that generate steam capable of turning turbines that produce electric current. However, in practice, none of the options has been implemented. In Soviet Russia, in general, environmental attempts were confined to planning landscaping areas of Soviet cities and to an extent to reducing the impact of industrial pollution on the environment. Those were only the first steps in the development of green architecture [3].

In the West, during the 1970s energy crisis and an increase in global fuel prices that followed, there was a surge in interest in renewable energy sources, saving fuel and energy resources used for heating construction structures. During this period, there were a lot of projects for buildings that ran on solar energy [4].

In the 1980s, environmental problems got exacerbated. The negative impact on nature increased as there was more anthropogenic impact and the scientific and technical complex was experiencing an intense growth. Buildings emitted almost half of all carbon dioxide into the atmosphere, so the new imperative was to protect the natural world. Comprehensive environmental reconstruction projects got underway [5]. For instance, the solution of traditional issues facing landscape architecture is intertwined with environmental problems as environmental conditions must be accounted for in order to create a sustainable urban environment. As the situation of the urban landscape is being exarcebated by the oversaturation of technology and the corresponding displacement of natural components, it is becoming critical to maintain harmonious and environmentally friendly areas. Hence considerable efforts have been made in order to rehabilitate and improve the environment [6].

A while later there were new trends in the formation of a green space, "...now nature is being „built" into the building." The flora is becoming one of the elements in the improvement and development of urban ecosystems. There is a new trend emerging — non-traditional design (greening flat roofs, including elements of the biotic environment in the architecture and interior of buildings: living plants; water; stone; materials imitating the wood texture; fragments of specific natural areas with a maintained microclimate, etc.) [7].

Fig. 1 shows the Quai Branly Museum in Paris completed in 2006, which is a wild, disorganized jumble of colorful boxes. In order to enhance the sense of confusion, the glass wall blurs the boundary between the exterior streetscape and the interior garden. Passers-by cannot tell the reflections of the trees from the blurred images behind the wall. The French architect Jean Nouvel is head of the project. It is designed in line with the principles of ecological architecture.

Fig. 1. Quai Branly Museum, Paris[1]

The concept of eco-architecture involves the use of processes that are responsible for the environment, the effective use of resources throughout the life cycle of a building, which is its complete ongoing design, operation and disassembly, including such stages as mining and production of building materials, design, construction of the building, its functioning, including the supply of water, gas, electricity, waste disposal, routine maintenance, possible reconstruction, disassembly following the end of the life cycle and reuse of the resulting materials [8].

Materials and Methods. The analysis of the environmental components of a construction site precedes construction, reconstruction as well as repairs of buildings and structures involving identifying the nature, intensity, and degree of danger this activity poses to the environment and public health. The aim of the analysis is to prevent environmental damage, as well as to ensure environmental safety, protection, sensible use and reproduction of natural resources given national, public and private interests.

[1] *Quai Branly Museum, Paris.* URL: https://www.thoughtco.com/buildings-and-projects-by-jean-nouvel-4065275 (accessed: 16.04.2025)

In order to develop environmental principles for designing construction facilities, it is essential to identify environmental impact factors of construction. The direct negative impact is increased noise, various radiations, and emission of harmful substances. The indirect impact lies in the fact that construction sites, buildings, structures, and roads annually occupy more and more vital space for humans.

The factors affecting the environment at each stage of building construction will be analyzed. During the construction phase, e.g., the most considerable negative impacts on the environment are as follows:

– atmospheric air pollution caused by gas and dust emissions (construction machinery and vehicles, welding and paintwork, etc.);

– contamination of groundwater and wastewater (refueling of machinery and vehicles, spills of concrete mix and various mortars, etc.);

– negative impacts on the acoustic environment (construction machinery, pile work, etc.);

– environmental pollution from construction waste;

– violation of the natural landscape of the area

– removal of soil following excavation which was stored in landfills (alienates territories, transforms the landscape, generates erosion);

– increasing the amount of household waste;

– impact on animals, birds, fish, and their habitats.

At the stage of building operation, there are the following negative impacts:

– disruption of the regime of illumination of the Earth's surface by the sun (insolation);

– disruption of the wind regime;

– violation of the hydrological regime of the area;

– reducing the amount of vegetation;

– soil and water pollution;

– dust, thermal pollution;

– increased traffic flows and thus the effect on the acoustic environment.

In case a building is to undergo reconstruction, a negative impact will come from the air, surface, groundwater, vegetation pollution, waste generation and noise pollution with the impact of the reconstructed facility on adjacent buildings accounted for.

For a more complete assessment of an impact of a project on the environment, its components are typically analyzed: climate and microclimate, airspace, geological layers, reservoirs, soil, flora and fauna, historical and cultural heritage, social and man-made environment.

All of this makes it necessary to come up with special environmental protection measures to ensure an ecological balance between man and nature, as well as sustainable development of construction areas and adjacent areas as well as cities in general. This is what is realized in the designing and constructing the entire life cycle of a building as a single chain. An analysis is crucial as it allows one to address lots of issues occurring at the design, planning, construction and other stages. After all, each stage is made up of lots of elements with incorrectly selected materials or design solutions possibly increasing the costs due to low energy efficiency. It is necessary to account for the environmental aspect in an analysis as legislation is tightening environmental standards and requirements. This is why choosing materials and technologies wisely determines how serious a footprint the project will leave in the environment will be. The use of the principles of eco-architecture is thus particularly poignant.

For instance, the use of a building life cycle analysis methodology, LCA (Life Cycle Assessment), is being widely implemented, which includes multiple steps: from collecting initial data to interpreting it [9, 10].

LCA life cycle analysis is a comprehensive methodology for assessing the full life cycle of a product, equipment, building, or system. It covers all stages (from extraction of raw materials to disposal), revealing the impact on costs, productivity and the environment [11]. This helps determine which of these needs attention: environmental friendliness, costs, productivity, and environmental impact.

The issues of ecological construction and building maintenance are critical in solving a city's environmental problems. This is being addressed worldwide [12, 13]. As a result, the construction industry is witnessing some changes making it possible to reduce the impact on the environment and use natural resources sensibly.

The quality of life in a city is starting being characterized by the number of buildings certified according to international "green" standards, such as The Leadership in Energy & Environmental Design (LEED) developed back in 1993. It was followed by lots of new certification standards: from the British BREEAM, the American WELL and Fitwel, and others to the Russian "Green Standards" and Green Zoom [14].

Green certification provides an opportunity not only to implement a construction project, accounting for environmental criteria, but also contributes to improving performance at all stages of a building's life cycle: from design and construction to commissioning and subsequent disposal.

In Russia, there are environmental standards NOSTROY 2.35.4–2011 "Green Construction", the Eco Village system for cottage areas, and the GREEN ZOOM standard. Also in 2009, Federal Law No. 261-FZ "On Energy Conservation and Energy Efficiency Improvement" came into force which generated a new system of state regulation in the area [15].

Research Results. A negative impact on ecosystems and saving various resources, particularly non-renewable ones, is reduced by creating conditions for the effective interaction of natural forms and man-made environmental objects. As a result, there is improvement and stabilization of the microclimate parameters inside the facilities being designed with the environment, which reduces energy consumption for the operation of the corresponding energy systems, and also retains and enhances the stability of the ecosystem the facilities being constructed are being implemented [16]. How exactly development and improvement of eco-architecture occur is guided by some principles. They are critical for effective realization of opportunities in developing urban environment.

The key principles of eco-architecture contributing to urban development are as follows:

1. The use of energy-saving technologies and alternative energy sources, which implies that of solar panels, wind turbines, as well as highly efficient heating and cooling systems in buildings [17].

Fig. 2 shows The Edge, a 15-storey office building in the Zuidas financial district in Amsterdam. It was built in 2015, with a total area of 40,000 m^2. The building has almost 30,000 sensors collecting anonymous data on heating and cooling systems, lighting, occupancy, etc. On 14 out of the 15 floors, the walls of the building can be freely moved enabling users to change the workspace as they please. The British rating agency BREEAM awarded the building a record-breaking 98.4% sustainability rating, which is the highest ever in its history.

Fig. 2. Office building in the business district of Zuidas[2]

[2] *Офисное здание The Edge. Dirk Verwoerd.* URL: https://archi.ru/projects/world/9650/ofisnoe-zdanie-the-edge (accessed: 16.04.2025)

2. Buildings should be designed with environmentally friendly materials as well as maintain energy efficiency and provide a longer service life to minimize waste and the need for permanent renovation. In order to create an eco-friendly environment, both previously unused and recycled materials can be used. On top of that, there are lots of alternative materials that are more environmentally friendly. The use of renewable and recyclable construction materials does not only help to reduce resource extraction, but also reduces carbon dioxide emissions through the course of construction [18].

Fig. 3 shows a solar power plant located on the roof of a building in Indonesia in Bontang. Such a solar power plant produces clean energy and reduces carbon emissions into the atmosphere. Its capacities cover up to 30% of the energy needs of office premises. The total area of the power plant is 6,500 m^2, and the capacity is more than 1,000 kW with an output voltage of 380 V.

Fig. 3. Location of a solar power plant on the roof of a building. Indonesia, Bontang, East Kalimantan[3]

a) *b)*

Fig. 4. Energy-efficient buildings using the green design concept: *a* — Chengdu, Southwest China, Minjiang River Valley[4]; *b* — Warsaw University Roof Garden[5]

[3] *Solar power plant on the roof of a building. Indonesia, Bontang.* URL: https://awsimages.detik.net.id/api/wm/2022/08/19/plts-atap-pkt-di-bontang_169.jpeg?wid=54&w=650&v=1&t=jpeg (accessed: 16.04.2025)
[4] *Energy-efficient buildings.* URL: https://ad009cdnb.archdaily.net/wp-content/uploads/2012/10/5078dce228ba0d1640000085_zcb-zero-carbon-building-ronald-lu-and-partners_zcb_01_and_one_planet_living_loop.jpg (accessed: 16.04.2025)
[5] *Warsaw University Roof Garden.* URL: https://i.pinimg.com/originals/bd/cf/77/bdcf77be7986fd3f72fec3c6038f7ede.jpg (accessed: 16.04.2025)

3. Designing a comfortable environment for humans. Green spaces and public parks are a key part of ecological urban planning. They serve to reduce noise and air pollution, improve residents' quality of life and contribute to the conservation of biodiversity. This is where a human can feel one with nature [19].

4. Conservation of biodiversity. The creation of ecological corridors, park areas, and vertical landscaping of buildings as shown in Fig. 5, helps preserve local ecosystems and plant and animal species inhabiting them, which is critical for maintaining the balance of natural processes and biological diversity [20].

Fig. 5. Modern landscape design[6]

5. Sensible waste management. Urban architectural solutions should come with waste collection and recycling systems in order to minimize a negative impact on the environment. It is also important to encourage waste separation among general public [21].

The Crystal building in London, UK (Fig. 6) is an exhibition center devoted to sustainable development and environmental responsibility. The building is equipped with photovoltaic and solar panels for generating electric energy, and also makes use of a waste disposal system and energy-efficient technologies.

6. Adaptability. Urban architecture should be flexible and able to adapt to changing climatic conditions and environmental issues. This includes the use of artificial intelligence, smart urban systems, and climate change forecasting for effective management of a city [22, 23].

Let us consider the fundamental principles (Table 1) guiding eco-architecture and enabling reduction of negative environmental impacts depending on the stage of the life cycle of a building [24].

[6] *Bæredygtig klimasikring hædret med betonbranchens Oscar*. URL: https://estatemedia.dk/dk/2023/06/02/baeredygtig-klimasikring-haedret-med-betonbranchens-oscar/ (accessed: 16.04.2025)

Fig. 6. The Crystal building, London, UK[7]

Table 1

Major paths of eco-architecture

Design stage	1. Accounting for the environment at all the stages — from design to demolition of a building. 2. Accounting for residents' quality of life at all the stages of construction. 3. A design allowing adaptation to the environment.
Construction stage	1. Use of low-carbon materials and technologies. 2. Effective and sensible use of available resources and renewable energy sources. 3. Restoration of the ecological balance in the surrounding areas. 4. Introduction of a waste management system. 5. Reuse of building resources and structural elements. 6. Use of non-toxic, sustainable materials.
Operation stage	1. Introduction of energy-saving technologies. 2. Introduction of a waste management system. 3. Reuse of building resources and structural elements.

The transition to sustainable urban development plays a key role in solving environmental problems facing cities. Lots of people associate the term "green" architecture with houses whose facades and roofs are completely covered with greenery, which is not the only way to make a building more environmentally friendly [25]. Hence buildings are constructed using natural materials, energy-saving technologies are actively used and the land allocated for building is made the best use of. Of course, there is still no mass demand for green architecture in Russia, but some technologies are

[7] *London: The Crystal is the world's greenest building.* URL: https://ru.baltic-review.com/2012/09/21/london-kristall-the-crystal-samoe-e-kologichnoe-zdanie-v-mire/ (accessed: 16.04.2025)

already in use. For example, reducing energy consumption by regulating heating, using motion sensors and LED lighting in the entrances of apartment buildings. In lots of countries, all of this has become well-known and commonplace, and environmental solutions have been complemented by rainwater treatment systems and roof gardens [26].

On top of that, the future of sustainable urban development depends on a host of factors, including technological innovation, political will, public participation, and global cooperation. The development of smart technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data opens up new avenues for optimizing urban processes, improving residents' quality of life, and reducing environmental impacts.

Residents' and communities' active engagement in planning and decision-making, as well as educational programs for raising awareness of the principles of sustainable development, are fundamental to attaining long-term goals.

Ultimately, the future of sustainable cities will rely on our ability to adapt to change, innovate, and work together for the common good.

Discussion and Conclusion. Eco-architecture naturally helps the planet by making sensible use of local materials and energy. Utilization of its principles enables reduction in environmental pollution, nature conservation and health maintenance.

The use of modern construction technologies and materials enables buildings that are more flexible and efficient in the field of sustainable architecture to be designed. On top of that, the combination of new technological capabilities and the experience gained in traditional architecture will allow for new solutions to ensure maximum functional efficiency, durability and cost-effectiveness at all the stages of the life cycle of a building.

References

1. Allakulyeva DM, Atayev ED, Atayeva AA Sustainable Construction: Eco-Architecture and Green Technologies. *Bulletin of Science.* 2024;10(79):970–973. (In Russ.) URL: https://cyberleninka.ru/article/n/ustoychivoe-stroitelstvo-eko-arhitektura-i-zelenye-tehnologii/viewer (accessed: 16.04.2025).

2. Emelianenko KM Ensuring Environmental Safety of Buildings. *Young Scientist.* 2018;5(191):20–22. (In Russ.) URL: https://moluch.ru/archive/191/48178 (accessed: 06.05.2025).

3. Rink J *Architecture: Ecotechnology and Sustainable Development in Practice.* (In Russ.) URL: https://www.houzz.ru/statyi/arhitektura-ekotehnologii-i-ustoychivoe-razvitie-na-praktike-stsetivw-vs~144254770 (accessed: 16.04.2025).

4. Ye Jiong, Zhang Ming, Zhu Dasha Some Thoughts on Ecodesign of Buildings. C*entral China Architecture.* 2009;27:47–51. https://doi.org/10.4324/9781315881348

5. Lan Zhang, Difei Zhao, Rui Li, Yingxing Chen Optimization of Urban Scenic Spot Planning Based on Ecological Chain and Reversed-Planning Theory — Using Yunlong Lake in Xuzhou City as an Example. *E3S Web Conf.* 2021;237:04036. https://doi.org/10.1051/e3sconf/202123704036

6. Enin AE, Akufuna K Basic Principles of Sustainable Design of an Artificial (Architectural) Living Environment. *Architectural Research.* 2017;1(9):71–79. URL: https://www.elibrary.ru/item.asp?id=29325053 (accessed: 16.04.2025). (In Russ.).

7. Belogolovsky V "Green Style" by Ken Yang. URL: https://archi.ru/press/world/25523/zelenyi (accessed: 16.04.2025) (In Russ.).

8. *Ecological Architecture: The Latest Architecture and News.* URL: https://www.archdaily.com/tag/ecological-architecture (accessed: 16.04.2025).

9. Mykh ME Architectural and Ecological Techniques of the 20th-21st Century. *Science Sphere.* 2021;7–2:35–39. https://doi.org/10.5281/zenodo.5144694

10. Cui Min P*reliminary Study of Environmental Building Design Strategies. Building Energy Conservation.* 2008;2:35–43.

11. Chernysh NA, Kushpaev AA Modern Trends in Eco-Architecture. *Problems of Engineering Graphic and Professional Education.* 2013;16(1). (In Russ.) https://doi.org/10.32523/2220-685X-2013-16-1-11-14

12. Davydova OV, Zuzemil DV Model of Interrelation of Nature, Man and Architecture. *Trends in Science and Education.* 2018;45-5:46–51. (In Russ.) https://doi.org/10.18411/lj-12-2018-114.

13. Guseva GV, Astafyev SA Integration of Information Modeling Technologies and the Internet of Things in Construction. *Baikal Research Journal.* 2020;11(3). (In Russ.)

14. Pijak J. *From Solar Art Installations to Self-Sustaining Homes*. URL: https://www.trendhunter.com/slideshow/2023-eco-architecture (accessed: 16.04.2025).

15. O'Keefe A. *10 Most Popular Eco-buildings in the World.* URL: https://manofmany.com/living/architecture/most-popular-eco-buildings-in-the-world (accessed: 16.04.2025).

16. Lezina YeG *Ecological Approach in Architecture.* (In Russ.) URL: https://izron.ru/articles/aktualnye-problemy-tekhnicheskikh-nauk-v-rossii-i-za-rubezhom-sbornik-nauchnykh-trudov-po-itogam-mezh/sektsiya-10-stroitelstvo-i-arkhitektura-spetsialnost-05-23-00/ekologicheskiy-podkhod-v-arkhitekture/ (accessed: 16.04.2025).

17. *Eco Brutalist Architecture: Green Meets Concrete.* URL: https://archeetect.com/eco-brutalist-architecture/ (accessed: 16.04.2025).

18. *43 Breathtaking Organic Architecture Concept Ideas 2024*. URL: https://sustainability-success.com/organic-architecture-concept-ideas/ (accessed: 16.04.2025).

19. Yushina SP Eco-Architecture. *Central Scientific Bulletin.* 2018;24(65):48. URL: http://cscb.su/n/032401/032401033.htm (accessed: 16.04.2025) (In Russ.).

20. Jain A *Eco-Futurism in Architecture: Harmonizing the Built and Natural Worlds*. URL: https://www.re-thinkingthefuture.com/narratives/a11932-eco-futurism-in-architecture-harmonizing-the-built-and-natural-worlds (accessed: 16.04.2025).

21. Lopez PJ *What is Biophilic Architecture? Seven Main Principles.* URL: https://www.render4tomorrow.com/what-is-biophilic-architecture (accessed: 16.04.2025).

22. *The Shape of Things to Come: Eco Architecture.* https://baku-magazine.com/home-page/eco-architecture/ (accessed: 16.04.2025).

23. *Eco-Architecture: a Green Tendency in the Construction Area.* URL: https://www.vreim.es/eco-architecture-a-green-tendency-in-the-construction-area/ (accessed: 16.04.2025).

24. Hohenadel K *What Is Sustainable Architecture? Environmentally Friendly Building: History, Characteristics, and Examples*. URL: https://www.thespruce.com/what-is-sustainable-architecture-4846497 (accessed: 16.04.2025).

25. Smirnov Smirnov EB, Datsyuk TA, Taurit VR Assessment of Environmental Safety of Buildings under Construction. *Water and Ecology: Problems and Solutions.* (In Russ.) 2017;3(71).82–99. https://doi.org/10.23968/2305-3488.2017.21.3.83-99

26. Rogova A Eco-Friendly Architecture: What it is and Why it is the Future. (In Russ.) URL: https://design-mate.ru/read/an-experience/green-architecture-and-future (accessed: 16.04.2025)

About the Authors:

Zhang Haoran, Master student of Shandong University, Shandong Jiaotong University (Jinan, Shandong Province, China), ORCID

Svetlana G. Sheina, Dr.Sci. (Eng.), Professor, Head of the Department of Urban Construction and Agriculture, Don State Technical University (162 Sotsialisticheskaya Str., Rostov-on-Don, 344003, Russian Federation) ScopusID, ORCID, rgsu-gsh@mail.ru

Vladimir V. Belash, Cand.Sci. (Eng.), Associate Professor of the Department of Urban Construction and Agriculture, Don State Technical University (162 Sotsialisticheskaya Str., Rostov-on-Don, 344003, Russian Federation), ScopusID, ORCID, rgsu-gsh@mail.ru

Claimed contributorship:

Z Haoran: development of the idea, research methodology, manuscript preparation, analysis and drawing conclusions

SG Sheina: scientific guidance, analysis and drawing conclusions

VV Belash: revision of the manuscript, revision 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.

Об авторах:

Чжан Хаожань, магистрант по направлению «Civil Engineering» Шаньдунского транспортного университета (Китайская народная республика, провинция Шаньдун г.Цзинань), ORCID

Светлана Георгиевна Шеина, доктор технических наук, профессор, заведующая кафедрой городского строительства и хозяйства Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, ул. Социалистическая, 162), ScopusID, ORCID, rgsu-gsh@mail.ru

Владимир Валентинович Белаш, кандидат технических наук, доцент кафедры городского строительства и хозяйства Донского государственного технического университета (344003, Российская Федерация г. Ростов-на-Дону, ул.Социалистическая,162), ScopusID, ORCID, rgsu-gsh@mail.ru

Заявленный вклад соавторов:

Чжан Хаожань: формирование основной концепции, методология исследования, подготовка текста, формирование выводов.

С.Г. Шеина: научное руководство, анализ результатов исследований.

В.В. Белаш: доработка текста, корректировка выводов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 17.04.2025

Reviewed / Поступила после рецензирования 12.05.2025

Accepted / Принята к публикации 28.05.2025

TECHNOLOGY AND ORGANIZATION OF CONSTRUCTION
ТЕХНОЛОГИЯ И ОРГАНИЗАЦИЯ СТРОИТЕЛЬСТВА

UDC 69.059
https://doi.org/10.23947/2949-1835-2025-4-2-96-105

Original Empirical Research

EDN: BWOMAF

Resource-Saving Technology for Dismantling the Supporting Decking of Reinforced Concrete Ribbed Slabs during Reconstruction and Demolition of Buildings

Elena A. Zholobova[1] ✉, **Alexandr L. Zholobov**[1], **Nadezhda A. Ivannikova**[2]
[1] Don State Technical University, Rostov-on-Don, Russian Federation
[2]Astrakhan State University of Architecture and Civil Engineering, Astrakhan, Russian Federation
✉ Elena@rniiakh.ru

Abstract

Introduction. Construction industry is currently in need of resource-saving technology that allows dismantling of coatings during reconstruction and demolition of buildings with maximum preservation of the integrity of reinforced concrete ribbed slabs for them to be possibly reused for their intended purpose, thereby not only preventing environmental pollution with construction waste, but also saving energy, labor and material resources for their disposal, as well as for reproduction of slabs.

Materials and Methods. While developing resource-saving technology, a set of methods and means for solving each of the tasks was used, including:

– visual inspection of reinforced concrete ribbed slabs during dismantling of the supporting deck of the roof in order to identify their suitability for them to be reused for their intended purpose;

– identification of the parameters of the equipment required in order to release seams and joints between slabs from mortar and concrete based on a study of the factors affecting the filling of seams and joints;

– identification of the parameters of special grips and devices for lifting ribbed slabs with damaged slinging loops using physical and computer models.

Results. As a result of the research, a new resource-saving technology for dismantling the load-bearing flooring of reinforced concrete ribbed slabs was proposed which is based on the methods developed by the authors:

- mechanical removal of the material filling the seams and joints between the slabs and the established parameters of the necessary equipment;
- release of the slabs from the existing connections with the rafter beams and cover trusses;
- testing of the remaining slinging loops of the slabs;
- slinging of slabs with damaged slinging loops with specially designed load-gripping devices.

Discussion and Conclusions. The new resource-saving technology allows dismantling the load-bearing reinforced concrete decking without additional damage to the slabs with them possibly being reused with a minimum amount of waste, saving labor and material resources, significantly reducing energy costs that would be required for the disposal of reinforcement waste and crushing concrete.

Keywords: reconstruction and demolition of buildings, dismantling of coatings, load-bearing reinforced concrete decking, ribbed slabs, monolithic seams and joints, sling loops

Acknowledgements. The authors appreciate the reviewers, whose critical assessment of the submitted materials and suggestions helped to significantly improve the quality of this article.

For citation. Zholobova EA, Zholobov AL, Ivannikova NA Resource-Saving Technology for Dismantling the Supporting Decking of Reinforced Concrete Ribbed Slabs during Reconstruction and Demolition of Buildings. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):96–105. https://doi.org/10.23947/2949-1835-2025-4-2-96-105

Оригинальное эмпирическое исследование

Ресурсосберегающая технология демонтажа несущего настила покрытий из железобетонных ребристых плит при реконструкции и сносе зданий

Е.А. Жолобова[1] ✉, А.Л. Жолобов[1], Н.А. Иванникова[2]
[1]Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
[2]Астраханский архитектурно-строительный университет, г. Астрахань, Российская Федерация
✉ Elena@rniiakh.ru

Аннотация
Введение. Строительное производство в настоящее время нуждается в ресурсосберегающей технологии, позволяющей производить при реконструкции и сносе зданий демонтаж покрытий с максимальным сохранением целостности железобетонных ребристых плит для возможности их повторного использования по прямому назначению, тем самым не только предотвращая загрязнение окружающей среды строительными отходами, но и сберегая энергетические, трудовые и материальные ресурсы на их утилизацию, а также на воспроизводство плит.
Материалы и методы. При разработке ресурсосберегающей технологии был применен комплекс методов и средств решения поставленных задач, в том числе:
– визуальное обследование железобетонных ребристых плит в процессе разборки несущего настила покрытия для определения их пригодности для повторного использования по прямому назначению;
– определение параметров оборудования, необходимого для освобождения швов и стыков между плитами от раствора и бетона на основе изучения факторов, влияющих на заполняемость швов и стыков;
– определение с помощью физических и компьютерных моделей параметров специальных захватов и приспособлений для подъема ребристых плит с поврежденными строповочными петлями.
Результаты исследования. В результате выполненного исследования предложена новая ресурсосберегающая технология демонтажа несущего настила покрытий из железобетонных ребристых плит, в основу которой положены разработанные авторами методы:
– механическое удаление материала заполнения швов и стыков между плитами и установление параметров необходимого оборудования;
– освобождение плит от имеющихся связей со стропильными балками и фермами покрытия;
– испытание сохранившихся строповочных петель у плит;
– строповка плит с поврежденными строповочными петлями специально сконструированными грузозахватными устройствами.
Обсуждение и заключение. Новая ресурсосберегающая технология позволяет производить демонтаж несущего железобетонного настила покрытий без дополнительного повреждения плит с возможностью повторного их использования с минимальным количеством отходов, экономя при этом трудовые и материальные ресурсы, в разы снижая энергозатраты, которые потребовались бы на утилизацию отходов арматуры и дробление бетона.

Ключевые слова: реконструкция и снос зданий, демонтаж покрытий, несущий железобетонный настил, ребристые плиты, замоноличенные швы и стыки, строповочные петли

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

Для цитирования. Жолобова Е.А., Жолобов А.Л., Иванникова Н.А. Ресурсосберегающая технология демонтажа несущего настила покрытий из железобетонных ребристых плит при реконструкции и сносе зданий. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):96–105. https://doi.org/10.23947/2949-1835-2025-4-2-96-105

Introduction. The production of precast reinforced concrete structures is a highly material-intensive, labor-intensive and energy-consuming process. Costly reinforcement products requiring significant energy consumption to be made as well as high-quality cements are used in their manufacturing.

Ribbed coating plates are leading the way when it comes to the volume of production of precast reinforced concrete structures. In compliance with GOST 9491-60 "Large-Panel Reinforced Concrete Ribbed Prestressed Slabs Sized 1.5×6 m for Coatings of Industrial Buildings" in this country from 1960 to 1978, reinforced concrete ribbed slabs of the same standard size — 1.5×6 m were produced for coatings of industrial buildings. Such slabs have a thin shelf (30 mm thick) and narrow ribs, which explains why the thickness of the protective layer in lots of places has a minimum allowable value of 10 mm. It is such coating plates that are most commonly found at reconstructed industrial facilities of capital construction. Under normal operating conditions, reinforced concrete load-bearing floor coverings, as well as other internal reinforced concrete structures of buildings, are capable of remaining operational for more than 150 years [1]. There is information available that after many years of operation in a non-aggressive environment, the strength of the concrete of the ribbed coating plates does not decline, but actually sees a slight increase with the reinforcement retaining its properties [2–3].

In case of reconstruction of buildings, it is frequently essential to partially or completely dismantle the load-bearing flooring in good condition of the ribbed plates, e.g.:

– to be used in covering lighting and light-aeration lanterns, as well as mounting openings;

– while replacing existing slabs with those with increased load-bearing capacity or with special holes;

– during the demolition of a building or its components.

With large amounts of demolition work on buildings with a precast reinforced concrete frame, the load-bearing flooring is commonly dismantled along with the frame using the collapse method of the so-called "concrete destroyers" based on tracked excavators with an elongated boom using hydraulic grinders as a working body [4–6]. The volume of waste generated is beyond that of disassembled structures, and it is measured in tens of thousands of tons nationwide [7]. Researchers from Denmark found that during the disposal of these wastes, 2 times as much carbon dioxide is released into the atmosphere than during the reuse of the coating plates obtained during dismantling of reinforced concrete flooring [8].

In spite of attempts made by scientists and specialists to come up with efficient technological solutions, it has been impossible to cut down the amount of waste as much as possible by piecemeal dismantling of reinforced concrete load-bearing flooring of ribbed slabs for them to be possibly reused for their intended purpose, due to permanent, hard-to-reach welded joints in sealed seams and joints between slabs, as well as to the massive damage of their sling loops [9–10].

In order to provide construction production with a resource-saving technology allowing dismantling of reinforced concrete flooring with maximum preservation of the integrity of the ribbed slabs, thereby not only preventing environmental pollution from construction waste, but also saving energy, labor and material resources for their disposal and reproduction, a study was carried out at the Department of Technology of Construction Production of the Don State Technical University to identify opportunities for:

– improving the method of removing mortar and concrete from joints and spaces between ribbed slabs;

– using slinging loops while slinging ribbed plates for lifting or developing special grips;

– increasing productivity and safety of dismantling flooring of ribbed slabs;

– expanding the field of reuse of ribbed coating plates.

Materials and Methods. The parameters of the resource-saving technology for dismantling the load-bearing flooring of building coverings, as well as equipment and technological equipment for its use, directly depend on the shape and size of the ribs, as well as the slinging loops of the reinforced concrete ribbed slab shown in Fig. 1.

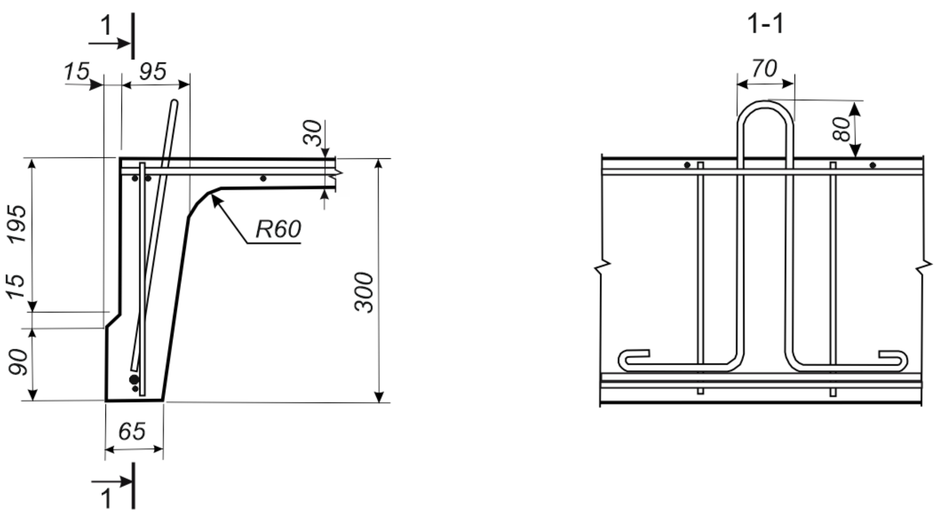


Fig. 1. Dimensions of the longitudinal ribs and slinging loops of the coating plates in compliance with GOST 9491-60

Accounting for these dimensions, the depth and possible thicknesses of the joints between the plates, the shape and dimensions of the grippers for slinging plates with damaged slinging loops, and the dimensions of the release wedge for tearing adjacent plates from each other were identified.

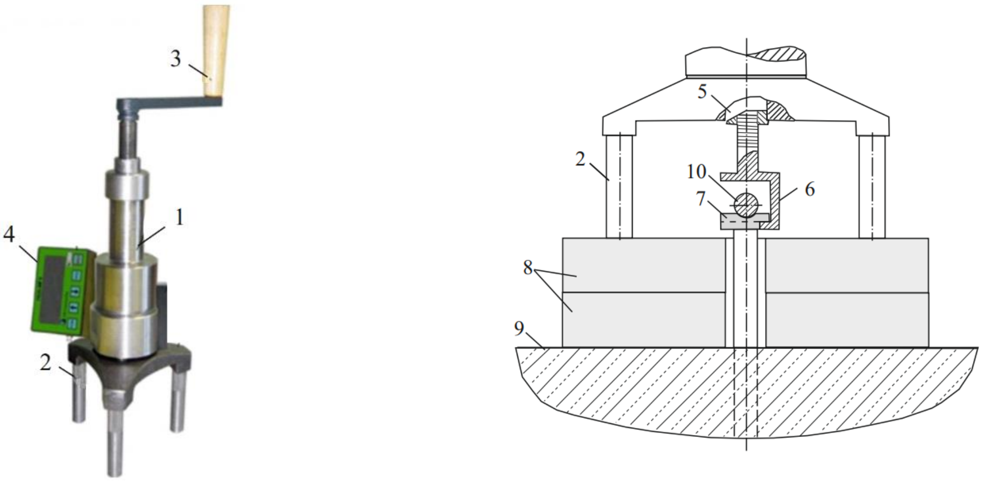
In order to identify the optimal parameters of the resource-saving technology being developed, as well as the necessary equipment and tools, a set of methods and tools for solving each of the above tasks shown in Table 1 was applied.

Table 1

Methods and tools used in solving the problems of developing a resource-saving technology for dismantling load-bearing flooring of buildings made of reinforced concrete ribbed slabs

Tasks of investigating the opportunities	Research methods	Research tools
Improving the method of removing mortar and concrete from joints and spaces between slabs	Analytical: – questionnaire; – identification of factors impacting the fillability of seams and joints	–
	Instrumental: checking the fillability of seams	Electric perforator with a drill bit with a diameter of 5 mm and a working length of 250 mm (as a depth gauge)
	Instrumental: identifying the adhesion of the solution	PSO-10MG4AD device (Fig. 2 *a*)
Using sling loops for lifting	Instrumental: checking the load-bearing capacity of the sling loops under a load of 10 kN	Same
Detecting plate defects before lifting	Visual inspection according to GOST 31937-2024 "Buildings and Structures"	–
Increasing productivity and safety of dismantling the ribbed flooring	Physical and computer modeling of grippers for slinging ribbed plates	Physical and computer models of grips
Expanding the area of reuse of coating plates	Analytical: – classification of ribbed slabs according to their condition; – studying the experience of reuse of slabs accounting for their technical condition	–

The load-bearing capacity of the sling loops was checked using a PSO-10MG4AD device based on aluminum plates with a total thickness corresponding to the height of the sling loop as shown in Fig. 2 *b*.



a) *b)*

Fig. 2. General view of the PSO-10MG4AD device (*a*) and the scheme of its application when checking the strength of sling loops (*b*): 1 — force exciter; 2 — support; 3 — loading handle; 4 — electronic unit; 5 — rod of the force exciter; 6 — gripper; 7 — lodgment; 8 — aluminum plate; 9 — coating plate; 10 – sling loop

Research Results. According to the analysis of the results of studying domestic and foreign experience in dismantling precast reinforced concrete floors of building coverings, at least 50% of ribbed slabs experience additional damage during dismantling, and about half occur due to the rupture of sling loops. In 5–15% of the slabs, the ribs are damaged while seams and joints between the slabs are being cleaned using a mechanized impact tool, and in the remainder, while holes are being punched in the corners of the slabs for access to the welded joints of the slabs at their resting points on rafter trusses or beams.

Hence due to rib chips formed during dismantling of load-bearing flooring, in particular at their end sections, as well as cracks, most of the coating plates are typically abandoned and disposed of as waste. It has also been found that in order to lift slabs, holes are most commonly punched in the shelf of ribbed slabs near damaged sling loops for two loop slings to pass resulting in a decrease in the load-bearing capacity of the slab.

Inspection of the side faces of the ribbed slabs after dismantling the flooring, as well as the results of selective drilling of holes in the joints between the slabs showed that the seams were mostly filled with mortar to a depth of 5–15 cm (Fig. 3 *a*). This might be due to the lack of requirements for the mobility of the mortar for sealing joints, as well as their low controllability.

It was fairly rarely that the seam turned out to be filled up to the ledges of the longitudinal ribs of the slabs, i.e., 20 cm deep. These are typical for ridge sections of a coating where the upper part of the seam opens by 90 mm at the standard slope of the upper faces of the double-pitched rafter beams 1:12 (Fig. 3 *b*). It is to be noted that even in these cases, the solution barely penetrated into the lower part of the seam between the ledges of the longitudinal ribs of the plates, just as with the usual opening of the upper part of the seam — by 40 mm. (Fig. 3 *a*).

Along the roof endowment, the seams between the slabs of the coating turn out to be completely unfilled owing to the lack of access to its cavity from above the slab. (Fig. 3 *c*).

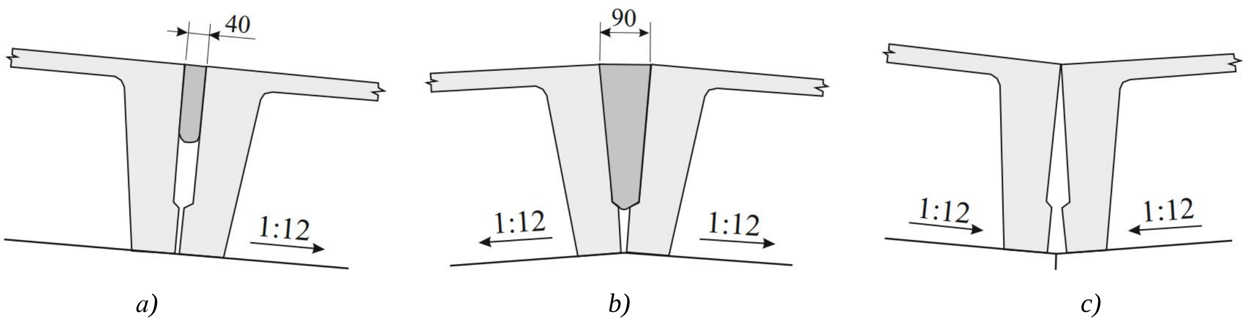


Fig. 3. Shape and size of the cross-section of the seams between the ribbed plates: *a* — regular seam*; b* — expanded seam; *c* — closed seam

Being aware of these features enabled us to identify the required cutting depth of the seam, which should correspond to the height of the upper (expanded) part of the longitudinal seam and be equal to 200 mm. This should prevent accidental damage to the ledges in the longitudinal ribs of the slabs by the rotating diamond cutter disc. In order to perform this technological operation, a seam cutter with a maximum cutting depth of 200 mm can be recommended, e.g., the TSS RH-500G brand, its general view is shown in Fig. 4.

Fig. 4. General view of the TSS RH-500G seam cutter with the diamond disc removed

Through the course of the study, the amount of adhesion of the solution to the side faces of the slabs was identified for 16 of them at four different sites. A large variation of these values (from 0 to 0.4 MPa) was observed, which can be accounted for by the lack of any instructions on the preliminary preparation of the slab faces for improving the adhesion of the mortar.

The resulting data enables us to conclude that after the slab has been freed from the welded joints with the rafter structures and at least the joints and seams between the slabs from mortar and concrete have been partially freed, the outermost slab in the row before lifting can be easily moved away from the adjacent slab using a self-contained wedge of the KRA1150 brand with a force of up to 10 kN, its general view is shown in Fig. 5, or two mounting crowbars.

Fig. 5. General view of the self-contained release wedge of the KRA1150 brand

At the next stage, the authors looked at the possibility of pre-evaluating the suitability of the slab for reuse before they had been lifted, even during dismantling of the flooring. With no visible defects, such as exposed reinforcement, cracks in the longitudinal ribs, deep chips of the lower edges and corners of the ribs, as well as rust spots and areas of concrete leaching, the slabs can be used for their intended purpose — when new or reconstructed coatings are being installed.

If there are minor defects, the plates can be used as permanent formwork for the construction of ribbed basement floors with increased load-bearing capacity in industrial buildings erected on peat and permafrost soils. If the edges of the slabs experience considerable damage with their shelf retaining its integrity, it is recommended that such slabs are used for installing temporary sidewalks and footpaths on construction sites. Other than that, the slabs must be recycled into crushed stone with scrap metal being separated.

The biggest challenge facing builders while dismantling decking is the most sling loops being non-operational and might break while a slab is being lifted. GOST 9491-60 for reinforced concrete ribbed slabs provided for slinging loops made of round hot-rolled reinforcement with a diameter of 10 mm. They should be positioned 1 m away from the end face of the plate.

As a result of investigating the experience of dismantling precast reinforced concrete load-bearing flooring and its individual parts, it was found that the most common damages experienced by sling loops are steel corrosion and mechanical destruction during construction while bent by blows of a sledgehammer at the bend point (flattening of steel, fracture). The statistical data collected and processed by the authors on the most common causes of sling loops being non-operational are shown in Table 2.

For mechanical testing of sling loops 70-80 mm high with a force of 10 kN, the authors employed the PSO-10MG4AD device mounted above each loop on several aluminum plates (20 mm thick with a rectangular hole sized 100 × 20 mm for the sling loop) used as a lining for the device, and a steel base for supporting the loop.

As a result of testing the sling loops (after the unbending), it was found that only 43% of the total number of straightened loops were able to withstand the specified load. I.e., at least two of the four hinges in each slab are at risk of being damaged while it is being lifted, and hinges that have been damaged are known to be beyond repair.

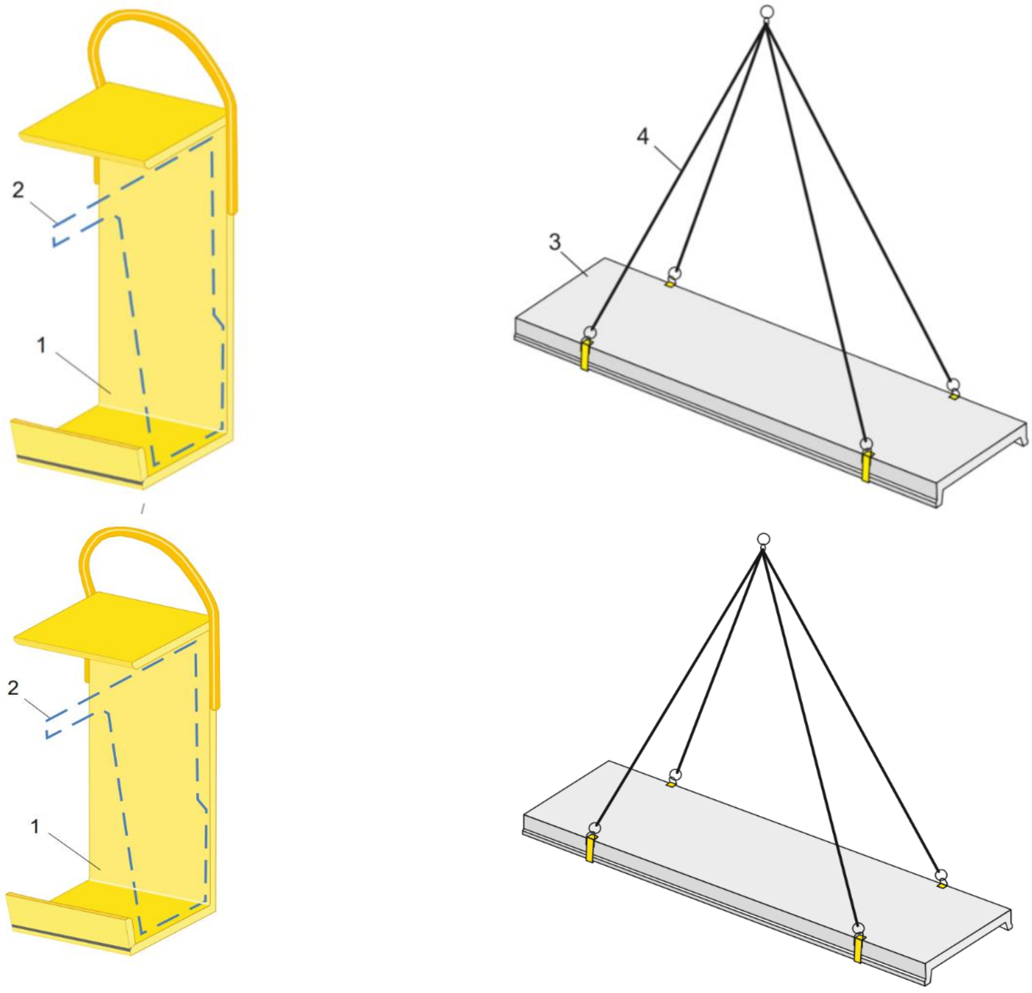
In order to make sure there can be slinging of plates with damaged slinging loops, the authors developed a special lifting device using computer and physical models named a sliding support grip in compliance with the classification given in GOST R 58520-2019 "Lifting Tools". The gripper is designed for a load-bearing capacity of 20 kN and can be used multiple times, as well as for reliable protection against uncontrolled disconnection from the plate.

Table 2

The most common causes of non-operability of slinging loops in reinforced concrete ribbed slabs

Causes of non-operability of sling loops	Conditions of causes of non-operability of sling loops	Average frequency of the cause, %
Significant corrosion of a sling loop material	Accumulation of atmospheric moisture in the coating thickness under the most vulnerable areas of the roof (under the eaves and overhangs), as well as where there is no vapor barrier or it was incompletely applied	15
Deformation of a cross section of a sling loop	The use of a sledgehammer while bending the hinges after laying the slabs in the design position	5
A bend with a radius of curvature of less than 5 mm	The same	25
Cracks and raptures	The same	8
The diameter of the reinforcement is less than 10 mm in compliance with GOST 9491-60	Factory defect occurring while a plate was being reinforced	5
No sling loops	The hinges were cut off after the slabs had been laid in the design position while the coating was being installed	11

The main gripper element is made of a 36P channel shorty in compliance with GOST 8240-97 "Hot-Rolled Steel Channels" with a length of 100 mm and a mass of no more than 10 kg. The grippers must be installed at the pre-cut slinging loops, i.e., at a distance of 1 m from the ends of the plate, as shown in Fig. 6 *b*.



a) *b)*

Fig. 6. General view of the sliding support gripper (*a*) and the loop-free slinging scheme of the coating plates (*b*): 1 — sliding support gripper; 2 — contour of the cross-section of the longitudinal rib of the plate; 3 — ribbed plate sized 1.5×6 m; 4 — four-branched sling

According to the results of a production inspection, four sliding support grippers, temporarily installed on the ribbed plate, allow not only lifting and moving it to the storage location, but also positioning it in a new manner or on a transportation vehicle.

It is suggested that dismantling and the proper dismantling of the load-bearing flooring is prepared in the following order:

– the physical wear of reinforced concrete load-bearing flooring is identified according to the signs of wear such as cracks in the joints between the slabs, cracks in the slabs, traces of leaks or freezing on the slabs, noticeable deflections of the slabs with exposed reinforcement;

– the existing sling loops are cut off;

– cuts are made with a depth of 200 mm along the longitudinal seams and transverse joints between the ribbed plates using a seam cutter, e.g., TSS RH-500G brand, with a diamond disc with a diameter of 500 mm;

– free access is provided to all of the three welded embedded parts of each coating plate, the load-bearing flooring in the span or cell should be dismantled in the reverse order to the way it was installed while the building was under construction. At the same time, plates can be freed from welds by means of an angle grinder or gas cutting equipment;

– plates with visible defects are identified that are unacceptable in compliance with GOST 9491-60 with the appropriate marking made;

– before a slab is lifted, it is made sure that it is completely released from attachment to the truss or beam of the coating by shifting from the adjacent slab along the supporting rafter structures by means of a sliding self-contained wedge KR2,5120 or two 20-30 mm mounting crowbars.;

– a slab is evaluated for further use in four possible ways;

– by means of a rack and pinion jack with a lifting capacity of 1-2 tons, free end of the plate by 20 mm is lifted by the end rib and two wooden pads are placed under it;

– on each longitudinal edge of the coating plate two sliding support grips are installed at a distance of 1 m from the ends of the plate;

– using a crane equipped with a four-branch sling, the plate is slung by the loops of the grippers, lifted and moved to the temporary storage area of the plates in compliance with the chosen direction of their further use.

The slabs should be evaluated after the dismantling of the load-bearing flooring based on the results of their loading tests in compliance with GOST 8829-2018 "Reinforced Concrete and Factory-Made Construction Products. Loading Test Methods".

While single-floor industrial buildings are under reconstruction, cutting welds and installing one of the ends of the plate on wooden linings is recommended from the mounting cradle of the hydraulic lift. The hazardous area for dismantling the load-bearing flooring must be fenced at the floor or ground level.

The above technological capabilities were validated over the years during the reconstruction and demolition of capital construction facilities in the cities of Rostov-on-Don, Astrakhan and Arkhangelsk. At the same time, the authors made use of the data from a questionnaire and expert assessments conducted by specialists with relevant experience in dismantling reinforced concrete structures of buildings.

Discussion and Conclusion. The study has allowed us to do the following:

– to justify the possibility and rational behind mechanized removal of mortar and fine-grained concrete from the joints between the coating plates with no damage to their edges to the depth of the existing groove by means of a 200 mm deep seam cutter;

– to prove the use of the known methods of slinging ribbed slabs during the dismantling of precast reinforced concrete load-bearing flooring of building coverings dangerous and inefficient. An alternative method of slinging has been set forth using the retractable support grips developed by the authors;

– expand the scale of possible use of coating plates in the presence of minor defects as permanent formwork for ribbed basement reinforced concrete floors and large-sized paving slabs.

Therefore as a result, a new resource-saving technology has been developed that allows dismantling of the load-bearing reinforced concrete flooring with no additional damage to the slabs with possible reuse with minimal waste, while saving labor and material resources, considerably cutting down the energy consumption for disposal of reinforcement waste and concrete crushing.

The resource-saving technology of dismantling the load-bearing flooring of reinforced concrete ribbed slabs is set to be in common use in restorating damaged buildings in the territories of the Russia’s new territories liberated during the special military operation.

References

1. Falikman VR, Stepanova VF Normative Service Life of Concrete and Reinforced Concrete Structures and Principles of their Design According to Durability Parameters. *Industrial and Civil Engineering.* 2019;6:13–22. (In Russ) https://doi.org/10.33622/0869-7019.2019.06.13-22

2. Halding PS, Negendahl K The Potential for Direct Reuse of Precast Concrete Slabs in Buildings with "Wet" Joints. *Eighth International Symposium On Life-Cycle Civil Engineering.* 2023:3158-3165. https://doi.org/10.1201/9781003323020-385

3. Zemlyanskij AA, Zhukov AN, Bulavina DA Experience of Field Testing of Reinforced Concrete Ribbed Slabs. *Building Sciences.* 2019;4:79–82. (In Russ.) https://doi.org/10.25628/UNIIP.2019.43.4.014

4. Kuzhin MF, Alhamd A Research of Organizational and Technological Solutions in the Demolition (Dismantling) of Buildings and Structures. *Construction Production.* 2022;2:57–60. (In Russ). URL: https://doi.org/10.54950/26585340_2022_2_57

5. Vetrova OA Methods of Disposal of Construction Waste from Dismantling Structures of Two Industrial Buildings. *Engineering Journal of Don.* 2024;4(112):693–703. (In Russ) URL: http://www.ivdon.ru/ru/magazine/archive/n4y2024/9147 (accessed: 27.03.2025).

6. Küpfer C, Fivet C Panorama of Approaches to Reuse Concrete Pieces: Identification and Critical Comparison. *Journal of Physics: Conference Series.* 2023;19(2600):192006 https://doi.org/10.1088/1742-6596/2600/19/192006

7. Widmer N, Bastien-Masse M, Fivet C Building Structures Made of Reused Cut Reinforced Concrete Slabs and Walls: a Case Study. *Life-Cycle of Structures and Infrastructure Systems.* 2023:172–179. https://doi.org/10.1201/9781003323020-18

8. Kovalenko SO Recycling and Reuse of Building Materials Resulting from the Dismantling of Buildings and Structures. *Components of Scientific and Technological Progress.* 2023;11(89):78–83. (In Russ).

9. Halding PS Design for Bisassembly of Concrete Slabs with Mortar Joints. *Buildings.* 2023;8(13):1957. https://doi.org/10.3390/buildings13081957

10. Ishchenko AV, Tverdohlebova EA An Overview of Modern Technologies for the Disposal of Construction Waste. *Engineering Journal of Don.* 2024;3(111):1–13. (In Russ). URL: http://ivdon.ru/ru/magazine/archive/n3y2024/9083 (accessed: 27.03.2025).

11. Kodysh EN Dismantling of Buildings and Structures with Deep Processing of Demolition Products. *Industrial and Civil Engineering.* 2023;10:64–69. (In Russ) URL: https://doi.org/10.33622/0869-7019.2023.10.64-69

About the Authors:

Elena A. Zholobova, Cand.Sci. (Eng.), Associate Professor of the Department of Construction Production Technology of the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ScopusID, ORCID, Elena@rniiakh.ru

Alexandr L. Zholobov, Cand.Sci. (Eng.), Associate Professor of the Department of Construction Production Technology at the Don State Technical University (344003, 1 Gagarin Square, Russian Federation, Rostov-on-Don,), Associate Professor, ScopusID, ORCID, info@rniiakh.ru

Nadezhda A. Ivannikova, Cand.Sci. (Eng.), Associate Professor of the Department of Industrial and Civil Engineering at Astrakhan State University of Architecture and Civil Engineering (18 Tatishcheva St., Astrakhan, 414056, Russian Federation), ScopusID, ORCID, buildinst@mail.ru

Contributorship:

EA Zholobova: formation of the main concept, goals, objectives of the study and its general planning, preparation of the manuscript, revision and development of the conclusions.

AL Zholobov: review of the sources, analysis and generalization of the results obtained, revision of the manuscript, design of the illustrations.

NA Ivannikova: participation in the implementation of the research, analysis of the results, revision of the manuscript, formulation of the conclusions.

Conflict of interest: The authors declare no conflict of interest.

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

Об авторах:

Елена Александровна Жолобова, кандидат технических наук, доцент кафедры технологии строительного производства Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, ORCID, Elena@rniiakh.ru

Александр Леонидович Жолобов, кандидат технических наук, доцент кафедры технологии строительного производства Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, ORCID, info@rniiakh.ru

Надежда Александровна Иванникова, кандидат технических наук, доцент кафедры промышленного и гражданского строительства Астраханского государственного архитектурно-строительного университета (414056, Российская Федерация, г. Астрахань, ул. Татищева, 18), ScopusID, ORCID, buildinst@mail.ru

Заявленный вклад авторов:

Е.А. Жолобова: формирование рабочей гипотезы, цели и задачи исследования, подготовка текста, доработка и развитие выводов;

А.Л. Жолобов: обзор литературных источников, анализ и обобщение результатов исследования, доработка текста, оформление иллюстраций;

Н.А. Иванникова: участие в реализации исследования, анализ полученных результатов, корректировка текста, формулирование выводов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 30.03.2025
Reviewed / Поступила после рецензирования 17.04.2025
Accepted / Принята к публикации 06.05.2025

TECHNOLOGY AND ORGANIZATION OF CONSTRUCTION

ТЕХНОЛОГИЯ И ОРГАНИЗАЦИЯ СТРОИТЕЛЬСТВА

UDC 627.8.05
https://doi.org/10.23947/2949-1835-2025-4-2-106-116

Original Empirical Research

EDN: DEMQTY

Implementation of Machine Learning Models in the Construction Site Organization Process

Svetlana E. Manzhilevskaya ✉
Don State Technical University, Rostov-on-Don, Russian Federation
✉ smanzhilevskaya@yandex.ru

Abstract

Introduction. Strategic planning is important for effectiveness of investment and construction projects. Complexity of solving problems increases with growth of variables in calculations and constraints. For effective planning of construction sites, many factors need to be taken into account, such as spatial constraints and distances between objects. To solve such problems, it is possible to use a mathematical machine learning model – a genetic algorithm (GA) to optimize the placement of objects on a construction site. The aim of this study is to improve the accuracy and flexibility of solutions in the organization of the construction site, reduce complexity of calculations and minimize the amount of data.

Materials and Methods. The realization of this goal is possible by introducing the Systematic layout planning (SLP) method into the planning process to optimize space on construction sites. To confirm the effectiveness of optimizing the location of objects, the SLP method was applied in the organization of planning the construction site of an administrative building. The planning took into account the stages of work, the required economic facilities, data on safety and environmental safety of the construction site. The use of the Dynamo plugin for analysis made it possible to adjust the location of objects taking into account the utilization factor of the territory.

Research Results. As a result of the modeling of the construction site plan, it was found that using the SLP method, the process is adapted, taking into account the location of objects according to the established values of the relationship matrix using automation and color coding to simplify analysis. Flexibility in making informed decisions is important for designers, given the safety and intensity of the workflow. The SLP method reduces distances through optimization of logistics, optimizes the location of objects on the construction site, taking into account restrictions. This hybrid approach increases the efficiency of implementing machine learning models in the design process of building master plans of facilities. The integration of the genetic algorithm and BIM technologies into the construction site organization process helps to optimize solutions based on optimal distances, improves the visualization of decisions and problem correction.

Discussion and Conclusions. The results of the study contribute to decision-making efficiently and quickly, minimizing the time required for analysis compared to some other approaches. The result of the research is the creation of a system that is not only flexible and adaptable, but also overcomes the limitations typical of previous methods. The use of machine learning technologies to predict optimal design decisions and automate the establishment of key relationships can significantly reduce the need for manual data entry, thereby simplifying and speeding up development processes. Adding new examples of diverse plans and spatial constraints will strengthen the foundations of the concept and enrich its application in a variety of investment and construction projects.

Keywords: construction organization, construction site, machine learning algorithms, artificial intelligence, end-to-end technologies

Acknowledgments. The authors would like to thank the editors and reviewers for their attentive attitude to the article and the above comments making it possible to improve its quality.

For citation. Manzhilevskaya S.E. Implementation of Machine Learning Models in the Construction Site Organization Process. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):106–116. https://doi.org/10.23947/2949-1835-2025-4-2-106-116

Оригинальное эмпирическое исследование

Применение моделей машинного обучения в процесс организации строительной площадки

С.Е. Манжилевская ✉

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉ smanzhilevskaya@yandex.ru

Аннотация

Введение. Стратегическое планирование важно для эффективности инвестиционно-строительных проектов. Сложность решения задач увеличивается с ростом переменных в расчетах и ограничений. Для эффективного планирования строительных площадок нужно учитывать множество факторов, таких как пространственные ограничения и расстояния между объектами. Для решения таких задач возможно применение математической модели машинного обучения — генетического алгоритма (GA) для оптимизации размещения объектов на строительном участке. Цель данного исследования — улучшение точности и гибкости решений в организации строительной площадки, уменьшение сложности вычислений и минимизация объема данных.

Материалы и методы. Реализация цели исследования возможна с помощью внедрения в процесс планирования метода Systematic layout planning (SLP) для оптимизации пространства на строительных площадках. Для подтверждения эффективности оптимизации расположения объектов метод SLP был применен в организации планирования строительной площадки административного здания. В планировании учитывали этапы производства работ, требуемые хозяйственные объекты, данные о технике безопасности и экологической безопасности территории строительства. Применение плагина Dynamo для анализа позволило скорректировать расположение объектов с учетом коэффициента использования территории.

Результаты исследования. В результате проведенного моделирования плана строительной площадки установлено, что с помощью метода SLP процесс происходит адаптировано, учитывая расположение объектов согласно установленным значениям матрицы взаимосвязей с помощью автоматизации и цветовой кодировки для упрощения анализа. Гибкость в принятии обоснованных решений важна для проектировщиков, учитывая безопасность и интенсивность рабочего процесса. Метод SLP сокращает расстояния через оптимизацию логистики, оптимизирует расположение объектов на строительной площадке с учетом ограничений. Этот гибридный подход повышает эффективность внедрения моделей машинного обучения в процесс проектирования строительных генеральных планов объектов. Интеграция генетического алгоритма и BIM-технологий в процесс организации строительной площадки помогает оптимизировать решения на основе оптимальных расстояний, совершенствует визуализацию принимаемых решений и корректировку проблем.

Обсуждение и заключение. Результаты проведенной работы способствуют эффективному и быстрому принятию решений при организации строительной площадки, минимизируя время, необходимое для анализа, по сравнению с другими подходами. В результате исследования создана система, которая не только гибка и поддается регулировке, но и преодолевает ограничения, характерные для предыдущих методов. Применение алгоритмов машинного обучения для прогнозирования оптимальных проектных решений и автоматизации установления ключевых связей может значительно уменьшить необходимость ввода данных вручную, тем самым упрощая и ускоряя процессы разработки. Добавление новых примеров разнообразных планов и пространственных ограничений укрепит основы концепции и обогатит ее применение в разнообразных инвестиционно-строительных проектах.

Ключевые слова: организация строительства, строительная площадка, алгоритмы машинного обучения, искусственный интеллект, сквозные технологии

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

Для цитирования. Манжилевская С.Е. Применение моделей машинного обучения в процесс организации строительной площадки. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):106–116. https://doi.org/10.23947/2949-1835-2025-4-2-106-116

Introduction. Strategic planning transforms a construction site into a highly organized mechanism where each element yields to the logic of optimal use of space, time and material resources. Innovative design methods enable the design of the most adaptive and efficient working environments [1].

The logistical efficiency of construction sites depends not only on the technical parameters, but also on the quality of the preliminary planning. There might be economic losses due to improper organization of the workspace creating delays and reducing the employees' overall productivity.

Construction site facilities are complex systems where every element — from access roads to internal infrastructure — has a key role to play in the overall concept of sustainable development. The major aspect is not just the physical location of the facilities, but their integration into the overall resource optimization strat egy in order to minimize unforeseen costs [2]. It is essential to realize that the initial planning of a construction site might have a dramatic impact on the final effectiveness of an investment and construction project, transforming investments into either considerable savings or additional unplanned costs.

The efficiency of the project enhances due to the competent planning of the location of economic facilities. This approach does not only serve to optimize working processes, but also creates a safe environment conducive to higher productivity levels. Unhindered movement around the facility and uninterrupted operation become possible if the space is thoroughly organized, which ultimately leads to a higher overall performance and maneuverability on the site.

According to the theory of algorithms, organization of space on a construction site belongs to the category of NP-complete problems involving high computational complexity [3]. As the number of variables and constraints goes up, complexity of solving such problems rises, making it more daunting to identify the optimal location due to the rapid increase in the number of possible options. In particular, the development of effective plans for construction sites calls for a whole host of factors to be accounted for, including spatial constraints and the need to maintain certain distances between objects [4]. A variety of approaches can be employed in order to address such complex problems, including mathematical modeling, computer algorithms, and approaches based on rules and knowledge, each offering unique advantages for organizing space on a construction site [5].

While methods yielding the best results call for a great deal of computational effort and time, particularly while expanding tasks, heuristic approaches stand out for their ability to perform quick calculations and adaptability to new conditions and problems [6]. In spite of this, the major problem with heuristic methods is their inconsistency in delivering the best result, which might force one to have to strike a balance between speed and accuracy. In conditions where time is a crucial factor, particularly while working with large and complex tasks, it is customary to compromise choosing between the speed of calculations and the accuracy of the results [7].

As part of improving the efficiency of developing a construction site plan and optimal placement of facilities on it, it is recommended thatadvanced mathematical optimization techniques, particularly the "genetic algorithm" (GA), are used [8]. This optimization method is considered most suitable for planning the location of facilities on construction sites [9]. The genetic algorithm, inspired by the Darwinian theory of evolution, effectively deals with problems similar to the processes of natural selection and genetic changes making it possible to find the best options for space allocation [10].

What sets Algorithms based on genetics apart are their global search capability and efficiency in solving nonlinear problems of high complexity. However, their implementation can be confusing, and they typically perform slower in the search process [11]. This, in turn, increases the likelihood of algorithms reaching imperfect solutions even before a truly optimal answer has been identified.

While developing construction master plans, time-tested approaches are commonly used and based on past experience, as well as guided by specialized standards and regulations such as NOSTROI 2.33.52-20111 and SP 48.13330.20192 which contain construction sites standards instead of relying on mathematical methods. The implementation of innovative planning strategies in construction typically faces obstacles due to a range of factors. Existing mathematical approaches to planning offer only partial solutions that cannot adequately adapt to the changeable and unstable conditions typical of construction projects.

One of the major problems is the need for significant time for data processing by algorithms in their quest to identify ideal solutions, which becomes particularly pronounced as projects start growing in size and complexity. A tool for developing a construction site plan should be easy to use, capable of working with a limited amount of source data, and readily adaptable to a variety of construction projects and land plots. It should help to obtain results as soon as possible, while accounting for the key aspects such as the duration of transportation, safety of work and financial costs, minimizing the need for in-depth analysis for a better outcome.

In order to optimize the planning of the construction site, it is necessary to apply a hybrid approach combining professional experience, standards and strategies for optimizing space. Its aim is to improve the accuracy and flexibility of solutions, reduce computational complexity, and minimize the need for large amounts of data to be entered. In the context of streamlining work on construction sites, the hybrid mathematical optimization method Systematic layout planning (SLP), which is widely used in the organization of space in manufacturing enterprises and in the field of services (Fig. 1), acts as a logical optimization strategy [12].

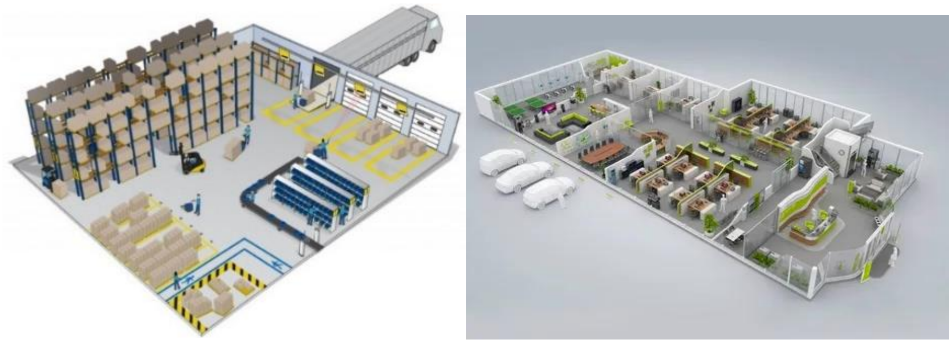


Fig. 1. Space optimization using the SLP method

The SLP method is unique as it allows the application of norms developed based on an in-depth analysis of the relationships between layout elements and their location. In turn, BIM technologies provide an opportunity to efficiently organize the construction process. The SLP principles focus on an integrated approach to the development of construction site plans, accounting for interactions of construction processes and optimal use of space. Using the Dynamo visual programming environment and Python automates processes and improves planning quality. The use of the Dynamo plugin in Revit enabled us to optimize layouts in a BIM environment providing real-time analysis.

Studies designed to analyze the effectiveness of SLP and GA methods demonstrate that hybrid approaches lead to successful results, despite being faced with some problems [13, 14].

In all of the analyses a specially developed method of arranging space was employed where the objects were arranged in an automated mode. The spatial volume rigidly corresponded to the needs for placing the simulated objects which were identical in size and shape. These analytical works enrich the practice with new information on the synthesis of different strategies for space organization, however, they indicate the need to increase the flexibility of planning processes.

The aim of this study is to improve the accuracy and flexibility of solutions in the organization of the construction site, reduce the complexity of calculations and minimize the amount of data.

Research Results. The use of technology to optimize the location of objects on a construction site through SLP (construction site layout optimization — CSLP) is key to effective expansion of available space by means of integrating elements into unused areas while observing a set of unique and interrelated tasks and co+nstraints. This approach to planning does not only increase the overall efficiency of land use, but also causes a reduction in design costs, reduces the need for transportation of building materials and provides a higher level of accessibility and safety for the employees on the site.

For a more in-depth understanding of CSLP, it is necessary to become familiar with some key terms including h the concepts of space, time and aspects of structuring occupy a special place. In the context of spatial analysis, special attention is paid to the three major methods of representing the work area. One involves the use of fixed locations, which greatly simplifies the CSLP process transforming it into a process of distributing objects to predefined positions. Another approach divides the territory into sections using a grid where each cell is equipped with a control point for effective use of every square meter for placing the objects.

In a method that recognizes space as continuous, objects can be placed anywhere in a specific area representing a continuous zone. However, this raises the complexity of the process, as it is necessary to make use of more complex algorithms in order to avoid conflicts between objects, and calls for more time for data processing.

Shapes such as cylinders and rectangles are employed to display objects on a construction site, which allows one to accurately determine the location and dimensions. This provides a clear idea of the available resources and facilities on the site. During the construction process, as the building is ready, the need for certain objects and the space they occupy changes, which directly affects how long they are used on the construction site.

In the context of temporary changes that might take place during construction, there are three modeling methods. One is static, which provides for the constant presence of all the facilities throughout the entire duration of the project ignoring any time fluctuations [15].

The use of a method that divides the construction production process into different periods and provides for the development of separate options at each stage serves to assist in overcoming some limitations. In contrast, the method that adapts to the actual time frame of each stage of construction and adjusts plans in accordance with current changes on the construction site differs from the sequential approach, where certain elements of the project remain unchanged over a few stages.

Parameter improvement strategies for CSLP modeling can be classified as accurate, experience-based (heuristic), and mixed methods.

Various approaches are used for the best results to be delivered. In the case of using methods based on precise calculations, objective functions are employed in order to identify ideal answers, but these are costly in terms of computing resources, which reduces their effectiveness in large-scale investment and construction projects. On the other hand, heuristic approaches are able to offer solutions that are close to ideal ones with no need to devote significant resources to identifying the absolute optimum. Combining these two approaches, hybrid methods use mathematical modeling and algorithmic strategies to improving the effectiveness of solutions. Optimization problems are formulated based on mathematical models includinge various quantitative analysis methods such as linear programming, integer programming, and mixed programming [16].

As the complexity of the task rises due to the increasing number of goals and constraints, the solution becomes significantly more time-consuming due to the exponential increase in complexity. Instead of focusing only on specific optimization goals, applying rules based on personal experience enables one to form guiding principles making the task easier for designers to deal with. Algorithms, in turn, are focused on identifying the best or near-best solutions for those optimization problems that are inherently highly complex, particularly in the context of computational complexity theory [17].

The SLP principles establish an approach to developing spatial plans through an integrated approach, starting with data analysis and ending with the selection of the optimal layout option. The methodology relies on the importance of understanding the interactions between different activities, as well as the need to identify the volume, shape and type of each allocated space. The effective combination of these facilities within the framework of the project allows achieving better planning results. Fig. 2 shows the sequence of SLP procedures with the results achieved at each stage.

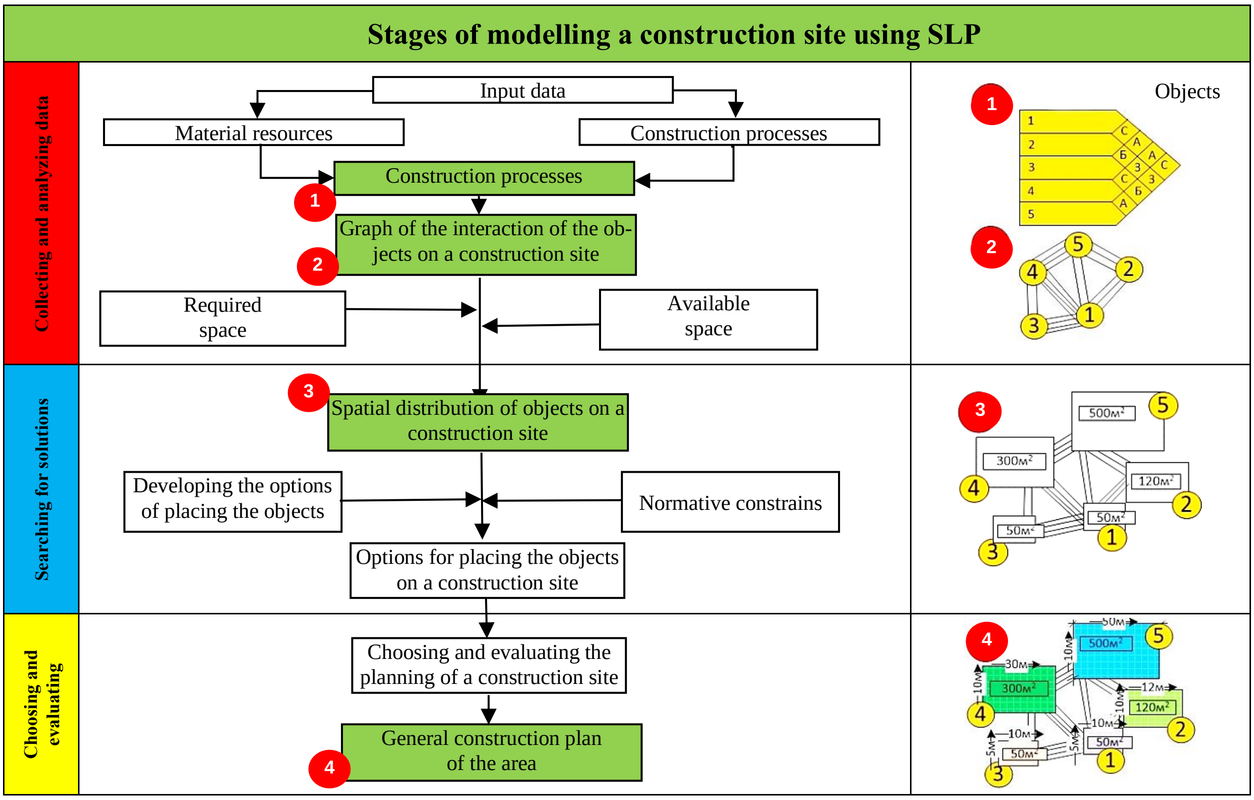


Fig. 2. Stages of construction site modeling using SLP

The SLP method is designed to optimize the building site space, which is not only functionally, but also rationally organized — from the initial stage of data analysis to the final layout. The multi-step process enables the designer to create balanced and thoughtful spatial concepts, building bridges between key objects to achieve the best results. At the very initial stage, the interaction of resource flows in different areas and their impact on areas of activity is assessed using preferred ways to visualize these relationships.

This method makes it easier to understand the connections between different objects by making it possible to design diagrams visualizing these connections via activity. In the graphs (Fig. 2), each diamond-like element shows the level of interconnection in numerical terms.

For SLP, certain designations of the levels of interrelation of objects were introduced: "A" — absolute, "S" — significant, "S" — standard, "A" — acceptable, "O" — optional and "U" — unacceptable. The number of lines between two elements reflects the degree of significance of their relationship.

What the designer does first is collect and analyze the data to develop a diagram that shows how the objects will interact with each other. This is followed by the second phase, where identifying the requirements for the area occupied by the object, the necessary equipment, mechanisms and the availability of free space to ensure optimal location is key. The analysis then proceeds to a stage where potential design changes are evaluated to identify the level of their feasibility and optimality, while taking into account costs, technical limitations and safety issues. The final stage of the design process is to analyze alternative locations and select the most appropriate one looking at both their advantages and disadvantages.

This study employs a design approach known as Design Science Research (DSR) whose results are called artifacts [18]. Design starts with a series of steps performed by a specialist designer with the aim of developing an artifact product. Creating an artifact provides the researcher with a more nuanced understanding of the problem, which helps to improve the design process by rethinking it. This evaluation and development process is commonly repeated multiple times until the final design artifact is completed. These artifacts are also important for developing theoretical approaches. As part of this project, a BIM technology-based platform was developed to optimize the planning of construction sites using SLP.

Fig. 3 shows the outline of the research project. The project is implemented in several stages: first, the issues are identified followed by the stage of proposals as well as development, an assessment is then carried out with the outcome at the final one. During each stage, specific steps were taken leading to the completion of the study, which ensures that the idea is successfully implemented.

Stages	Activity	Results
1 Identifying the problem	Identifying the research problem ↓ Familiarization with the normative guidelines for planning a construction site ↓ Studying, comparing and training in programming languages ↓	Systematize the knowledge on planning of a land plot as a construction production using the SLP
2 Decision-making	Organizing the macrostages based on the genetic algorithms of SLP procedures and algorithms ↓	Structuring a computational tool
3 Conducting research	Obtaining information from the normative documentation ↓ Preliminary development of the algorithm model ↓ Use of a mathematical model in the study ↓ Identifying the issues and constrains ↓	Developing a model based on the SLP method
4 Evaluating the research results	Correcting the solutions ↓ Testing the efficiency of a mathematical model ↓	Optimization of the project solutions
5 Conclusions of the research results	Research Results	Identfying the theoretical and practical importance of the study

Fig. 3. Plan of the study implementation

The Dynamo visual programming environment, the Python programming language and the Revit 2023 software package were used for data processing providing automation of CSLP processes. The Dynamo environment served as a platform for visual programming making it possible to create an information model for computing, thereby providing convenient and flexible management of software processes using a node system.

Python scripts were actively used in the processes of visual programming using the Dynamo environment for wider modeling capabilities. They were also used for complex tasks, e.g., optimizing layouts using a genetic algorithm. This approach in modeling allowed us to create lots of layout options, adjusting various parameters and selecting the most effective solutions. Interaction with the Revit software package through the Dynamo plugin provided a visual representation of optimized layouts in the BIM environment allowing for a thorough analysis and optimization of the planning process in real time.

The information model for the analysis was refined step by step as the results were adjusted, which contributed to its improvement and allowed for higher performance in the accuracy and efficiency. The meticulous study of the feedback contributed to the improvement of the functionality of the model, including the ability to adapt to difficult construction site conditions and develop optimal types of layouts. All of this resulted in a new, more reliable and flexible decision-making model that integrated SLP approaches and provided handy tools for assessing the degree of interconnection and importance of various elements and objects on the site.

First and foremost, a strategy was developed for plans for the territory of the building site based on design experience and regulatory documentation. Next, the connections were assessed between the various objects necessary for the location on the construction site, noting the importance of their mutual location, which generally made it possible to develop an optimal model for the location of objects on the construction site. Using the Dynamo software, an estimation tool was implemented that calculated the total length of paths between objects, accounting for the optimal distances and relative positions of these objects. Using genetic algorithms, the optimal location of the objects was selected after the program had automatically generated a reference plan. The progress was assessed using the DSR (Design Science Research) method. The differences between the initial and optimized plan were revealed due to the territory utilization coefficient, which indicated the degree of progress achieved by applying a reduced list of object interconnection levels in the SLP to four to assess the degree of significance of the connections where the model were encoded under the symbols "H" — high level, "M" — medium importance, "L" — low level of importance, and "U" is an undesirable interaction. The assessment of facility interactions took into account factors such as operational activities, safety, and management preferences, which may include, for example, management's desire to place temporary buildings near the entrance to the construction site to facilitate access. In the procedure for assessing the level of interrelation between objects, each degree of significance of the relationship was assessed on a scale with four levels: 0 — absent, 1 — minimal, 2 — medium and 3 — high. Combining these estimates resulted in a proximity index ranging from 0 (no need for interaction) to 3 (high need for interaction). The matrix of interrelations of objects is shown in Fig. 4.

Levels of the organization of the objects on a construction site	Entry	Storage of bulk materials	Semi-closed cement storage	Concrete mixing node	Closed storage	Storage for the fencing materials	Formwork storage	Area of large assembly of elements and structures	Temporary buildings	Construction quarter	Waste accumulation spot
Entry											
Storage of bulk materials	HHM1										
Semi-closed cement storage	HHH0	HHH0									
Concrete mixing node	HHH0	BHB3	BHB3								
Closed storage	HHH0	HHH0	HHH0	HHH0							
Storage for the fencing materials	CHC2	HHH0	MHB3	HHH0	HHH0						
Formwork storage	HHH0	HHH0	HHH0	HHH0	HHC1	HHC1					
Area of large assembly of elements and structures	HHH0	BHB3	HHH0	HHH0	BHB3	HHH0	HHH0				
Temporary buildings	HBB2	HHH0	HHH0	HHH0	HBB2	HHH0	HBB2	HHX0			
Construction quarter	BBB3	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0		
Waste accumulation spot	HHC1	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0	BBH1	HHH0	

Designation	Object consistency level
B	High
C	Medium
H	Low
X	Undesirable

Designation	Level of significance of the relationship
3	High
2	Medium
1	Minimal
0	Absent

Fig. 4. Matrix of interrelationships of objects on the construction site

Through the course of the study, the CSLP method was tested during the planning of the construction site. The site was modeled in order to compare the initial and optimized site plan, as a result of which the optimization efficiency was evaluated. The object of the study was a plot of 300 m^2 with a building area of 158 m^2 designed for construction of an administrative building.

At the initial stage of the development of the plan, special attention was paid to the consideration of structures under construction. Basic elements such as the workers' entry points and transportation of materials, as well as the distribution of the road network influenced the initial setup of the platform. In addition, an important and unchanging part of the planning was the mounting crane whose location required significant computing resources exceeding the capabilities of the algorithm used. In order to form a single space on the building site, 14 new facilities were added to the existing ones. These have a variety of dimensions limited by the minimum dimensions established by the design documentation. The compactness of the organization was prioritized making it possible to create a tightly connected matrix of relationships as seen in Fig. 5.

Levels of the organization of the objects on a construction site	Entry	Storage of bulk materials	Semi-closed cement storage	Cloakroom	Closed storage	Storage for the fencing materials	Formwork storage	Dining room	Temporary buildings	Construction quarter	Waste accumulation spot
Entry											
Storage of bulk materials	HHH0										
Semi-closed cement storage	HHH0	HHH0									
Cloakroom	BHB3	HHH0	HHH0								
Closed storage	CHC2	HHH0	HHH0								
Storage for the fencing materials	CHC2	HHH0	MHB3	HHH0	HHH0						
Formwork storage	HHH0	HHH0	HHH0	HHH0	HHC1	HHC1					
Dining room	BHB3	HHH0	HHH0	BHB3	HHH0	HHH0	HHH0				
Temporary buildings	HBB2	HHX0	HHX0	BHB3	HBB2	HHH0	HHX0	BHB3			
Construction quarter	BBB3	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0		
Waste accumulation spot	HHC1	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0	HHH0	BBH1	HHH0	

Fig. 5. Matrix of the interrelationships of objects on the construction site of an administrative building

Fig. 6 shows the initially designed plan of the construction site and the plan optimized by means of the CSLP method where various functional areas are highlighted in different colors: green — stationary facilities, red — production and warehouse facilities, yellow — temporary buildings.

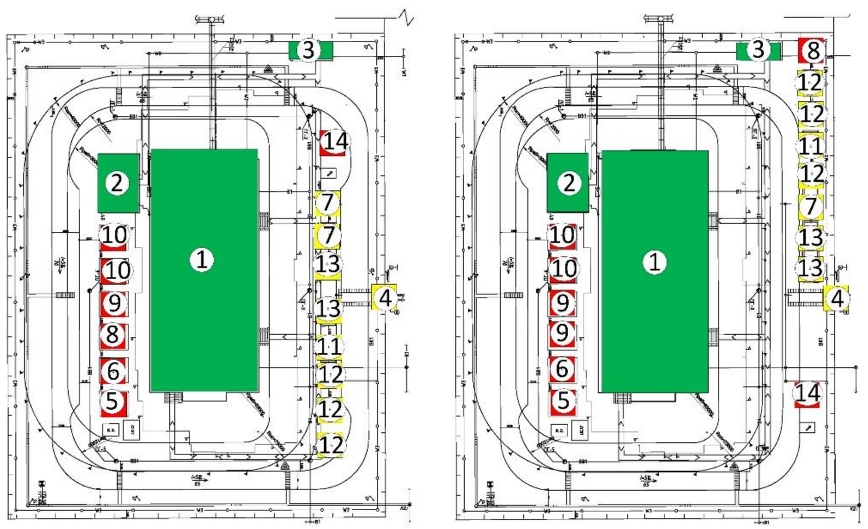


Fig. 6. Construction site layout: 1 — initial plan; 2 — optimized plan

The use of built-in Dynamo functions for analysis enabled the evaluation and adjustment of the location of the objects accounting for the territory utilization rate. Table 1 shows the calculation results and a comparison of the final values of the building coefficient for the two variants.

Table 1

Indicators of the construction site layout

Construction site planning	Coefficient of the area use
Initial	1.04
Optimized using the SLP method	1.2

Research Results. It was important for the CSLP process to adapt SLP procedures to better match the dynamics in the planning of construction sites that differ from static layouts. During the manufacturing process, SLP combines both stationary and mobile facilities, while temporary facilities in construction are moved during the course of work. CLP allows one to improve the SLP relationship matrix, making it more convenient and intuitive by automating and using colors to simplify relationship analysis. CSLP also accounts for the intensity of the workflow and safety aspects while determining the interconnection of facilities, which contributes to more efficient layouts accounting for the progress of the construction production.

Flexibility in making informed decisions is key for designers, as this enables them to consider the key factors such as safety and workflow intensity. The main goal of the SLP method is to reduce unnecessary distances through logistics optimization achieved by means of decision-making processes.

What makes the CSLP method different is that it allows optimization of the location of the objects on the construction site for any area in compliance with the restrictions. This hybrid approach reflects the designer's choice during planning and increases confidence in the tool, unlike the strict criteria of pre-established standards.

The integration of the genetic algorithm into the layout process makes it possible to implement a variety of solutions and optimizes them based on optimal distances significantly expanding the possibilities of layout. BIM technologies have a key role to play by providing visualization that improves the identification of problems and their subsequent correction. The combination of SLP with BIM technologies and genetic algorithms enables one to maintain the optimization logic adapting it to the layout of the construction site. Although real-time layout changes at various stages of construction production are not yet accounted for in the design standards, this approach significantly increases work efficiency and minimizes unnecessary movements.

Discussion and Conclusion. This paper presents an innovative approach to designing a collaborative computing environment that combines elements of strategic logistics planning (SLP) with the functionality of a BIM platform forming a unique hybrid system. The key advantage of the system is the visualization of the design process, focusing on the optimal organization of space for temporary facilities, accounting for such important aspects as workflow efficiency, safety and consideration of management preferences. The innovation of this approach is integration of decision-making mechanisms into the process of territorial distribution of administrative and economic facilities at the construction site, which ensures improved labor productivity through the competent organization of logistics at the facility. This hybrid model is able to combine machine learning algorithms with the involvement of expert experience, making it possible to efficiently generate various layout options with minimal requirements for source data, thereby speeding up the development process.

This platform makes use of modeling techniques that allow objects to occupy space with no reference to rigid coordinates or predefined grids. This enables the optimization of the use of each square meter by automatically calculating the optimal size of objects and their placement so that unnecessary occupied space is avoided. Effective adaptation and optimization of space directly affects the increase in labor productivity on the construction site, minimizing the occupied space on the building site and thereby financial costs.

The results of the work contribute to efficient and rapid decision-making, minimizing the time required for analysis unlike some other approaches. The result of the work is a system that is not only flexible and adaptable, but also overcomes the limitations found in previous methods. Unlike standard approaches that relied on standards or predefined templates, the suggested system operates within the framework of a model of unlimited space, which makes it possible to freely place elements. This approach provides designers with an unusually high level of control over setting constraints, selecting available space, and identifying access points.

The analysis conducted using CSLP to improve the layout of the land for the construction of an administrative building revealed that the possibilities for reducing inefficiently used space with no increasing costs vary depending on the size of the project and its complexity.

Depending on the complexity of the conditions for planning a construction site, a range of factors such as area restrictions, the variety and characteristics of facilities, the need for a specific location, fixed locations of some facilities, multi-level placement and non-standard shapes of sites might affect the ability of the platform to reduce unnecessary distances. Despite these challenges, the CSLP method can significantly improve performance in both simple and more complex environments. However, the effectiveness of this tool is limited by the quality of the source data and designer's active involvement in the process of identifying the relationships.

For successful design, it is necessary for developers to gain experience to help prevent possible miscalculations from occurring. However, it should be remembered that their personal views might unconsciously influence the final product, particularly in aspects related to establishing connections and interactions in the system.

In the future, the introduction of machine learning models into the design process can be significantly transformed by introducing optimization algorithms. They are designed to achieve a rational balance between speed and accuracy of data processing, which is critical for complex tasks. Using machine learning algorithms in order to predict optimal design decisions and automate the establishment of the key relationships can considerably reduce the need for manual data entry, thereby simplifying and speeding up development processes. Adding new examples of diverse plans and spatial constraints will strengthen the foundations of the concept and enrich its application in a whole range of investment and construction projects.

References

1. Xu M, Mei Z, Luo S, Tan Y Optimization Algorithms for Construction Site Layout Planning: A Systematic Literature Review. *Engineering, Construction and Architectural Management*. 2020;27:1913–1938. https://doi.org/10.1108/ECAM-08-2019-0457

2. Al Hawarneh A, Bendak S, Ghanim F Dynamic Facilities Planning Model for Large Scale Construction Projects. *Automation in Construction.* 2019;98:72–89. https://doi.org/10.1016/j.autcon.2018.11.021

3. Succar B Building Information Modelling Framework: A Research and Delivery Foundation for Industry Stakeholders. *Automation in Construction.* 2009;18(3):357–375. https://doi.org/10.1016/j.autcon.2008.10.003

4. Kaveh A, Vazirnia Y Construction Site Layout Planning Problem Using Metaheuristic Algorithms: A Comparative Study. *Iranian Journal of Science and Technology, Transactions of Civil Engineering.* 2019;43:105–115. https://doi.org/10.1007/s40996-018-0148-6

5. Jaafar K, Elbarkouky R, Kennedy J Construction Site Layout Optimization Model Considering Cost and Safety in a Dynamic Environment. *Asian Journal of Civil Engineering.* 2021;22:297–312. https://doi.org/10.1007/s42107-020-00314-3

6. Prayogo D, Cheng M-Y, Wu Y-W, Redi AANP, Yu VF, Persada SF at al. A Novel Hybrid Metaheuristic Algorithm for Optimization of Construction Management Site Layout Planning. *Algorithms.* 2020;13:117. https://doi.org/10.3390/a13050117

7. Yang B, Fang T, Luo X, Liu B, Dong M A BIM-Based Approach to Automated Prefabricated Building Construction Site Layout Planning. *KSCE Journal of Civil Engineering*. 2021;26:1535–1552. https://doi.org/10.1007/s12205-021-0746-x

8. Papadaki IN, Chassiakos AP Multi-Objective Construction Site Layout Planning Using Genetic Algorithms. *Procedia Engineering.* 2016;164:20–27. https://doi.org/10.1016/j.proeng.2016.11.587

9. Salah M, Elbeltagi E, Elsheikh A Optimization of Construction Site Layout Using BIM Generative Design. *International Journal of Construction Management*. 2024;24:314–322. https://doi.org/10.1080/15623599.2023.2222997

10. Chemim L, Sotsek N, Kleina M Layout Optimization Methods and Tools: A Systematic Literature Review. *Gestão da Produção, Operações e Sistemas*. 2021;16(4):59–81. https://doi.org/10.15675/gepros.v16i4.2806

11. Said H, El-Rayes K Optimizing Material Procurement and Storage on Construction Sites. *Journal of Construction Engineering and Management*. 2011;137:421–431. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000307

12. Maghfiroh MFN, Redi AANP, Ong J, Fikri MR Cuckoo Search Algorithm for Construction Site Layout Planning. *IAES International Journal of Artificial Intelligence*. 2023;12:851. https://doi.org/10.11591/ijai. v12.i2.pp851-860

13. Schwabe K, Teizer J, König M Applying Rule-Based Model-Checking to Construction Site Layout Planning Tasks. *Automation in Construction*. 2019;97:205–219. https://doi.org/10.1016/j.autcon.2018.10.012

14. Le PL, Dao TM, Chaabane A BIM-Based Framework for Temporary Facility Layout Planning in Construction Site: A Hybrid Approach. *Construction Innovation*. 2019;19:424–464. https://doi.org/10.1108/CI-06-2018-0052

15. Petroutsatou K, Apostolidis N, Zarkada A, Ntokou A Dynamic Planning of Construction Site for Linear Projects. *Infrastructures.* 2021;6:21. https://doi.org/10.3390/infrastructures6020021

16. Dienstknecht M A Branch and Bound Approach for the Tower Crane Selection and Positioning Problem with Respect to Mutual Interference. *4OR.* 2022;21:105–123. https://doi.org/10.1007/s10288-022-00503-7

17. Karmakar A, Singh AR, Kumar Delhi VS Automated Route Planning for Construction Site Utilizing Building Information Modeling. *Journal of Information Technology in Construction*. 2022;27:827–844. https://doi.org/10.36680/j.itcon.2022.040

18. Lacerda DP, Dresch A, Proença A, Antunes Júnior JAV Design Science Research: Método de Pesquisa para a Engenharia de Produção. *Gestão & Produção*. 2013;20(4):741–761. https://doi.org/10.1590/S0104-530X2013005000014

About the Author:

Svetlana E. Manzhilevskaya, Cand.Sci. (Eng.), Associate Professor of the Construction Management Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), ScopusID, ORCID, smanzhilevskaya@yandex.ru

Conflict of interest statement: **the author does not have any conflict of interest.**

The author has read and approved the final manuscript.

Об авторе:

Светлана Евгеньевна Манжилевская, кандидат технических наук, доцент кафедры организации строительства Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1) ORCID, ScopusID, smanzhilevskaya@yandex.ru

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

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 17.02.2025
Reviewed / Поступила после рецензирования 12.03.2025
Accepted / Принята к публикации 28.03.2025

URBAN PLANNING, PLANNING OF RURAL SETTLEMENTS

ГРАДОСТРОИТЕЛЬСТВО, ПЛАНИРОВКА СЕЛЬСКИХ НАСЕЛЕННЫХ ПУНКТОВ

UDC 69.022.5
https://doi.org/10.23947/2949-1835-2025-4-2-117-127

Original Empirical Research

EDN: HVZJMI

Standards for Green Roofs in Construction Projects

Svetlana G. Sheina[1], Ruslan V. Balashev[1] ✉, Roman D. Shakhiev[1], W. Shixiao[2]
[1]Don State Technical University, Rostov-on-Don, Russian Federation
[2] Shandong Jiaotong University, Jinan, Shandong Province, China People's Republic of China, Changqing District, Jinan
✉ ruslanbalashev33@gmail.com

Introduction. The study seeks to form a structured classification of green roofs essential for systematic development of practices of green architecture and natural urbanism in Russian development. The lack of a holistic approach to typologizing such solutions causes difficulties in designing and implementing environmentally oriented technologies. The system developed by the author covers four major characteristics and a set of sub-elements, which allows for a comprehensive description and differentiation of various types of green roofs. Such a classification can serve as an effective tool for specialists engaged in the field of design, construction and landscaping.

Materials and Methods. In order to look into the topic, a set of theoretical studies has been conducted. Regulatory documents, including GOST and SNiP, as well as international standards LEED and BREEAM, were examined. The works of specialists, practical examples and publications in specialized sources were also analyzed. The study describes an analysis algorithm: the investigation of constructive solutions, environmental characteristics, principles of design and operation. Green roofs are roofing structures with vegetation. Depending on their purpose, they are divided into exploited (for recreation and activities) and non-exploited (environmental functions). The construction of green roofs is regulated by such standards as GOST R 58875-2020, GOST R 54964-2012 and GOST R 58709-2019. These documents define the types of green roofs, requirements for materials, structures, and indoor climate.

Research Results. Throughout the course of the research, a typology was developed includg extensive, intensive and semi-extensive roofs, as well as classifications according to operational, structural, social and environmental criteria. Examples of implementation in international and Russian practice are provided. The classification allows one to account for the human use, placement and level of landscaping of roofs, offering a comprehensive description system.

Discussion and Conclusion. The introduction of green roof standards represents a totally new approach to building lifecycle management, including not only construction, but also environmental improvement, energy conservation, and quality of life, which is a lengthy and controversial process requring time for analysis and adaptation. They contribute to energy efficiency, thermoregulation, improved microclimate, extended roof life, and the creation of new recreational areas. The concept of green roofs is a synthesis of architecture, ecology and technology that can ensure the sustainable development of cities and improve the quality of life. The ultimate aim of this study is to offer a universal tool for typological analysis of green roofs which can be applied domestically to improve the effectiveness of urban planning solutions and sustainable urban environment development.

Keywords: classification of green roofs, types of roofs with landscaping, green roofs, hanging gardens, landscaping of actively used roofs, intensive and extensive landscaping, semi-intensive landscaping

For citation. Sheina S.G., Balashev R.V., Shakhiev R.D., Shixiao U. Standards of Green Roofs in Construction Projects. *Modern Trends in Construction, Urban and Territorial Planning.* 2025;4(2):117–127. https://doi.org/10.23947/2949-1835-2025-4-2-117-127

Оригинальное эмпирическое исследование

Стандарты зеленых крыш в объектах строительства

С.Г. Шеина[1], **Р.В. Балашев**[1] ✉, **Р.Д. Шахиев**[1], **У Шисяо**[2]

[1]Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

[2]Шаньдунский транспортный университет, провинция Шаньдун, г. Цзинань, Китайская народная республика

✉ ruslanbalashev33@gmail.com

Аннотация

Введение. Настоящее исследование направлено на формирование структурированной классификации озелененных кровель, необходимой для системного развития практик зеленой архитектуры и природного урбанизма в условиях российской застройки. Отсутствие целостного подхода к типологизации подобных решений создает сложности при проектировании и внедрении экологически ориентированных технологий. Разрабатываемая авторская система охватывает четыре ключевые характеристики и комплекс подэлементов, что позволяет комплексно описывать и разграничивать различные виды зеленых крыш. Такая классификация может служить эффективным инструментом в работе специалистов, занятых в области проектирования, строительства и благоустройства.

Материалы и методы. С целью раскрытия темы проведен комплекс теоретических исследований. Были изучены нормативные документы, включая ГОСТ и СНиП, а также международные стандарты LEED и BREEAM, проанализированы труды специалистов, практические примеры и публикации в специализированных источниках. В исследовании описан алгоритм анализа: изучение конструктивных решений, экологических характеристик, принципов проектирования и эксплуатации.

Зеленые крыши представляют собой кровельные конструкции с растительностью. В зависимости от назначения они делятся на эксплуатируемые (для отдыха и активностей) и неэксплуатируемые (экологические функции). Строительство зеленых крыш регулируется стандартами, такими как ГОСТ Р 58875-2020, ГОСТ Р 54964-2012 и ГОСТ Р 58709-2019. Эти документы определяют типы зеленых крыш, требования к материалам, конструкции и микроклимату помещений.

Результаты исследования. В процессе исследования разработана типология, включающая экстенсивные, интенсивные и полуэкстенсивные крыши, а также классификации по эксплуатационным, конструктивным, социальным и экологическим критериям. Представлены примеры реализации в международной и российской практике. Классификация позволяет учитывать человеческое использование, размещение и уровень озеленения кровель, предлагая комплексную систему описания.

Обсуждение и заключение. Внедрение стандартов зеленых крыш представляет собой принципиально новый подход к управлению жизненным циклом здания, включая не только строительство, но и улучшение экологичности, энергосбережение и повышение качества жизни, что является процессом длительным и противоречивым, требующим времени для анализа и адаптации. Они способствуют энергоэффективности, терморегуляции, улучшению микроклимата, продлению срока службы кровли и созданию новых рекреационных зон. Концепция зеленых крыш — это синтез архитектуры, экологии и технологий, способный обеспечить устойчивое развитие городов и улучшить качество жизни. Конечная цель данного исследования — предложить универсальный инструмент типологического анализа зеленых крыш, который может быть применен в российской практике для повышения эффективности градостроительных решений и устойчивого развития городской среды.

Ключевые слова: классификация зеленых кровель, виды крыш с озеленением, зеленые кровли, висячие сады, озеленение активно используемых кровель, интенсивное и экстенсивное озеленение, полуинтенсивное озеленение

Для цитирования. Шеина С.Г., Балашев Р.В., Шахиев Р.Д., Шисяо У. Стандарты зеленых крыш в объектах строительства. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2025;4(2):117–127. https://doi.org/10.23947/2949-1835-2025-4-2-117-127

Introduction. Modern challenges of urbanization and climate change are exacerbating the need for sustainable solutions for the urban environment. Green roofs are complex systems combining natural elements with engineering structures that can considerably improve the environmental and energy efficiency of buildings.

Despite the active development of technologies and positive international experience, there is no systematic classification of green roofs in domestic practice. Existing studies only look at individual design or functional aspects resulting in a lack of a unified approach in the design, evaluation and implementation of such solutions.

Hence there is a clear gap in the theoretical framework — the lack of a holistic typology of green roofs adapted to the domestic conditions. This stands in the way of adopting of the technology and makes it difficult for processes to be standardized.

The aim of the study is to develop a structured classification of green roofs that accounts for architectural and spatial parameters, functional purpose, landscaping intensity, social accessibility and technical characteristics applicable in the domestic climatic and regulatory conditions.

Materials and Methods. Green roofs are roof structures where vegetation is planted. Depending on their functional purpose, they are divided into exploited (intended for recreation, sports and other activities) and non-exploited (performing mainly environmental functions) ones. Designing such systems requires the use of integrated engineering solutions for improving energy efficiency, sustainability and environmental effectiveness of buildings [1].

As part of the study, a comprehensive theoretical analysis was performed including:

– review of regulatory documentation (including GOST standards, joint venture, international standards LEED, BREEAM);

– study of scientific publications on the design, operation and environmental aspects of green roofs;

– analysis of implemented facilities and standard solutions in different countries.

According to their functional purpose green roofs are classified into:

– exploited (used for recreation, sports, recreation);

– нnon-exploited (perform mainly engineering and environmental functions).

Below are the key technological directions in the construction of green roofs:

1. Layered structure and vegetation cover. The design of the green roof includes a few functional layers: waterproofing, drainage, filtering, substrate and vegetation (Fig. 1). Each uses specialized materials — from modern waterproofing membranes to light, nutritious substrates.

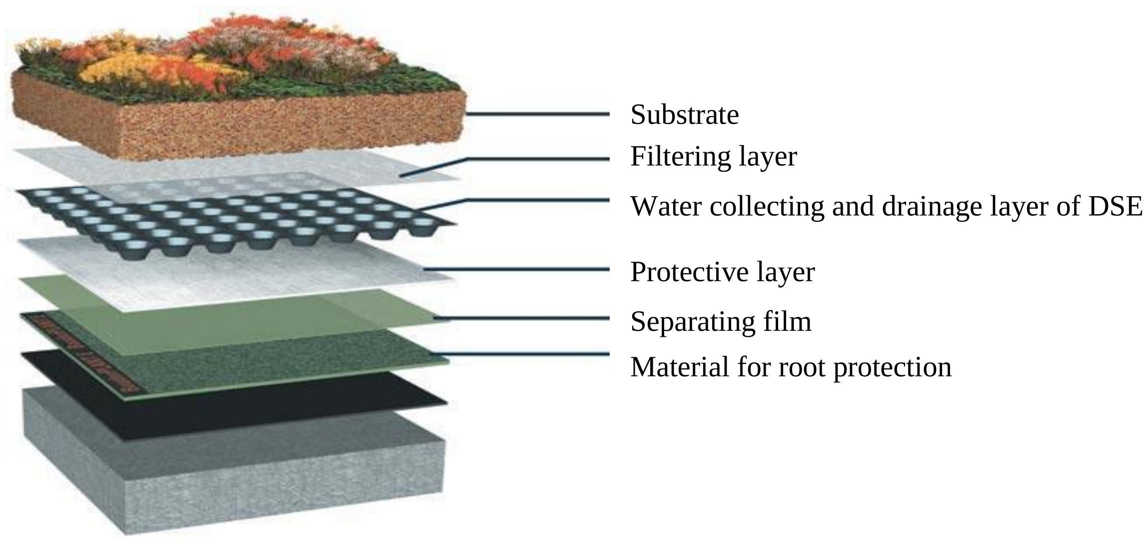


Fig. 1. Scheme of a green roof [1]

2. Water flow management. Effective distribution and use of precipitation is an important task. To this end, rainwater collection, accumulation and reuse systems are used, as well as technologies reducing the risk of moisture retention and damage to the waterproofing layer preventing leakage through roofing structures.

3. Improving energy efficiency. A green roof helps to reduce heat loss and overheating of buildings causing a reduction in air conditioning and heating costs. This is achieved due to the thermal insulation properties of the soil layer and can be complemented by energy—saving solutions, from solar panels to passive ventilation systems.

4. Air purification. Vegetation is involved in filtering pollutants and absorbing carbon dioxide. Particularly resistant plant species are selected that can improve air quality, especially in urban areas.

5. Supporting biodiversity. Green roofs can be adapted for creating microbiotopes. Solutions for attracting beneficial insects, birds and other representatives of fauna are employed.

6. Regulatory regulation. In order for green roof projects to be successfully implemented, it is necessary to comply with current building standards and regulations that define:

– the requirements for the composition of the soil layer, accounting for the stability and viability of plants;

– the parameters of drainage systems ensuring the normal removal of excess moisture;

– safety and structural reliability, including the permissible load on the building's load-bearing elements.

Standards and Regulation

In order to ensure the effectiveness of green roofs, there are standards and regulations that construction companies and architects use in order to create environmentally sustainable facilities [1]:

– soil layers and composition: specific standards regulate the types of soil used on green roofs to ensure not only aesthetic satisfaction, but also maximum vegetation viability.;

– drainage and sanitation: regulation includes drainage systems preventing excessive moisture retention and ensure normal rainwater runoff.;

– security systems: an important aspect is to ensure the safety and stability of green roofs, including weight management and structural integration.

In this country the regulatory regulation of green roofs relies on the following documents:

– GOST R 54964-2012 — establishes general requirements for the improvement of operational roofs;

– GOST R 58709-2019 — contains technical requirements and classification of green roofs;

– GOST R 58875-2020 — "the green standard" which defines the requirements for the environmental sustainability of buildings.

In compliance with the provisions of the GOST R 58709-2019 standard "Green Roofs. General Technical Requirements", the classification of green roofs includes the following main types:

– Garden roofs are those with perennial vegetation that are in need of systematic maintenance;

– Roofs with lawn covering are structures where stable herbaceous plants are planted;

– Roofs with container landscaping are surfaces that are landscaped by placing vegetation in mobile containers.

The standard also provides the requirements for the key components of a green roof (Fig. 2): structural elements (including the bearing capacity of the floor, waterproofing layers, drainage system, thermal insulation materials); used materials (their environmental safety, resistance to moisture, durability); plant communities (permissible species, their agrotechnical characteristics, seasonal sustainability).

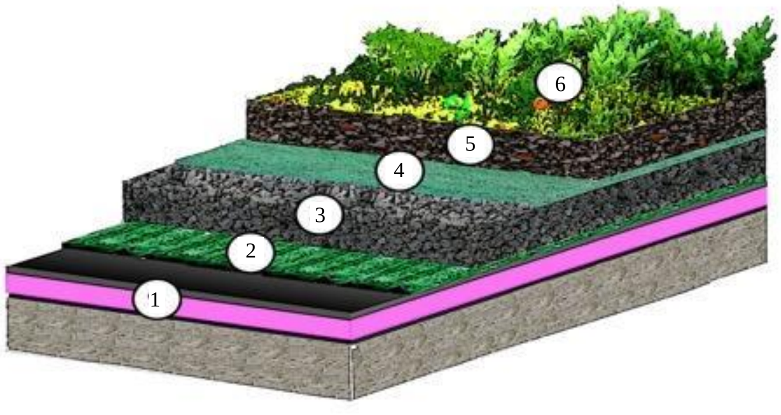


Fig. 2. Constructive solutions of the green roof:
1 — roof surface, waterproofing; 2 — protective and accumulating layers; 3 — drainage; 4 — protection from root germination; 5 — soil layer; 6 — plants [1]

Particular attention in the regulatory framework is paid to ensuring a favorable microclimate inside buildings. Hence according to GOST R 54964-2012, the temperature parameters in residential and public premises should range from 20 to 28°C at a relative humidity of 40 to 60%. Green roofs contribute to the thermoregulation of the interior of the building, reduction of the air temperature in the warmer months and thereby improvement of the microclimatic performance.

Research Results. The history of green roofs goes back a few decades when the technology has witnessed considerable changes. Approaches to standardization and classification of these structures were gradually formed. As a result of the gained experience, a unified typology of green roofs has been developed recognized by the international professional community, particularly by landscape architects.

The most common classification is based on the following criteria:

– load-bearing capacity of the roof;

– thickness and weight of the soil substrate;

– range and requirements for vegetation;

– the possibility and nature of human presence.

According to this typology, there are three major types:

1) extensive roofs — minimal maintenance, thin soil, weather-resistant plants;

2) intensive roofs are complex plantings including shrubs and trees that are in need of maintenance and reinforced construction;

3) semi-extensive roofs are an intermediate option combining elements of the two previous types.

The development of a classification system makes it possible to provide a comprehensive description of the types of green roofs, their purpose, design features and social accessibility.

The classification of green roofs in this study is considered as a systematic approach allowing a description of a complex multilevel structure of elements and their interrelationships. It is based on the interaction of three key components determining the architectural, spatial and functional organization of a green roof: the roof surface, human presence (use) and the vegetation layer. The ratio and degree of involvement of these elements make it possible to identify different types of green roofs as shown in the diagram (Fig. 3) [5].

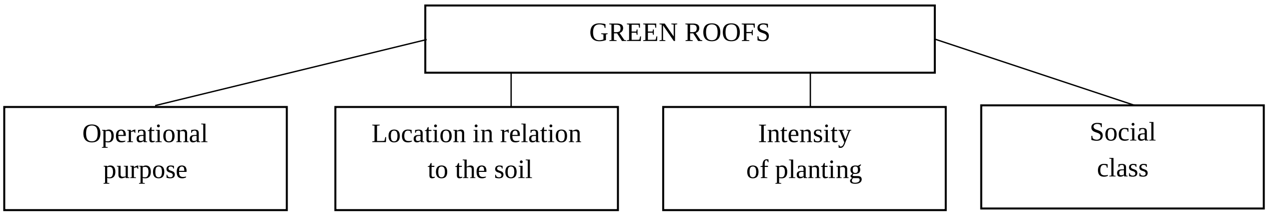


Fig. 3. Classification of green roofs by gender [5]

Deciding whether a person will use the roof for their own purposes is a key point in the natural classification of roofs. This classification includes the first aspect — the division into operational and non-operational roofs (Table 1).

Table 1

Classification according to the degree of exploitation

№	Type of green roofs	Description
1	Operated (without vehicle access)	Recreation areas, playgrounds, landscaped terraces (Fig. 4–7, 15)
2	Operated with the possibility of travel	Parking lots, roofs with walkways and access to equipment (Fig. 5, 9, 10)
3	Partially exploited	Used on separate sections of the roof
4	Unexploited	Perform only environmental and thermal insulation functions

The usable flat green roof offers a wide range of opportunities for recreation, physical development and rehabilitation. If the roof is completely covered with plants and a person is there only for maintenance (e.g., a gardener or a professional), such a roof is considered unused [5].

Depending on which type of green roof is being used, it performs various functions ranging from ecosystem-based (e.g., improving air quality or supporting biodiversity) to functional (e.g., creating space for recreation or sports). Let us consider the advantages of these species in the context of human interaction. Each type of green roof has its own characteristics depending on the specific needs of a building or an area. Operational roofs, e.g., provide additional opportunities for using space making them especially attractive in conditions of a limited urban area. Apart from the environmental and aesthetic advantages, different types of green roofs have functional features that depend on the degree of their operation. E.g., roofs intended for active use can be equipped to accommodate vehicles or install special equipment. It is to be noted that the operation of such roofs (e.g., for parking) is possible only in accordance with the terms of reference regulated by standards and building codes [5].

Green roofs are found on a variety of levels – on the ground, on the balcony, on the pedestrian passing and on the roof of the building, regardless of the number of floors (Table 2).

Table 2

Classification by location relative to ground level

№	Type of positioning	Examples and features
1	Green roofs of buildings	Roofs located on the upper floors of residential, public, and industrial buildings (Fig. 4)
2	Terraced roofs	Roofs located on the upper floors of buildings with terraces or terraced buildings (Fig. 6)
3	Roofs on underground levels	Roofs located on basements and ground floors of buildings, including various levels, above parking lots, shopping malls, and technical floors (Fig. 6, 11, 12)
4	Hanging gardens	Gardens located on various levels of above-ground parts of buildings, special platforms, bridges and overpasses (Fig. 8, 9)

Landscaped exploited roofs and gardens typically belong to different owners – from municipalities and owner associations to private individuals forming their social accessibility (Table 3).

Table 3

Classification by social affiliation (access)

№	Type of social accessibility	Description
1	Public operated roofs	publicly accessible, multifunctional territories with a high recreational load reducing the total area of landscaping and requires the sustainability of the plant assortment used (Fig. 7)
2	Private green roofs and terraces	Penthouses, villas, clubhouses (Fig. 16-17). Plants of different types are used depending on the needs of the owner, the general style, but accounting for the climate, wind load and care options in accordance with design standards.
3	Public green terraces	Operational green terraces of public buildings are designed for recreation and recreation, various types of landscaping provided in special containers and flowerpots. (Fig. 6)
4	Private landscaped terraces	Operational green terraces in private properties decorate historical and modern buildings, enriching the urban environment with a variety of plants and high-quality maintenance. (Fig. 17)

Green roofs and gardens are becoming accessible to both municipalities and homeowners' associations or individuals, which serves as a proof of their social importance. Besides, such roofs have an impact not only on improving the urban environment, but also on tackling environmental problems related to the influence of the technosphere. In one of the studies performed in order to identify the vulnerability of cities, it was found that the biosphere can play a major role in balancing the impact of the technosphere and the economy. E.g., in some European countries, the temperature of traditional roofs in summer can reach as high as 90 °C, while on green roofs it does not go beyond 50 °C, which can dramatically reduce the thermal impact on the environment. Hence the temperature difference between conventional and green roofs can be over 40 ° C, which makes the latter an effective tool in combating overheating of urban areas.

Green roofs can vary significantly — from lawns to planting trees and shrubs. The classification function "greening intensity" allows one to identify a few main categories (Table 4) [9].

Table 4

Classification according to the intensity of landscaping

№	Type of a green roof	Characteristics
1	Hanging gardens	High density, large plants, including trees and shrubs, producing the impression of a garden on a natural landscape (Fig. 8, 9)
2	Celestial oases	They occupy upper floors or flat roofs concentrated in the thick of the urban landscape, with rich plantings of various textures. They are approaching mini-squares and public spaces in scale (Fig. 5)
3	Earthly paradises	They are located on the Earth's surface: on the roofs of underground structures, parking lots, parks, etc. (Fig. 10-12). Landscaping with trees, shrubs and flowers is used to produce the impression of a garden.
4	Sparse landscapes	Green roofs on artificial bases are sparse plantings of lawns, meadows and shrubs (Fig. 11). The key function is recreation, sports, transit traffic. They are particularly relevant for courtyards, business and shopping complexes.
5	Extensive roofs	Flat or curved structures covered with a single layer of lawns, groundcover, or meadow plants. They serve ecological and aesthetic purposes and are not designed for permanent residence (Fig. 13)
6	Water worlds	They are created on artificial grounds to improve the microclimate. Water is the main theme of the project. Ponds, cascades are water elements for a microclimate (Fig. 14)

Fig. 4. Children's playground on the roof on the roof of a multi-storey parking lot. Copenhagen (2018) [8]

Fig. 5. Underground parking roof garden, Baden-Baden (2019) [8]

Fig. 6. Terraced house and green terraces. Arch. Bjarke Ingels Group. Copenhagen (2018) [8]

FIg. 7. Garibaldi Square - green roof in use, Milan (2016) [8]

Fig. 8. Hanging garden. Tsarskoe Selo (18th century, 2017) [8]

Fig .9. Hanging garden above De Sants Metro Station, Barcelona (2022) [8]

Fig. 10. Ground-level park - Zaryadye Park Moscow (2021) [8]

Fig. 11. Lawns of the operational roof of the shopping center on Amsterdam’s Museum Square (2013) [8]

Fig. 12. Schouwburgplein Square on the parking roof. Architect West 8. Rotterdam (2013) [8]

Fig. 13. Green roof of the Museum of Modern Art. Frankfurt am Main (2016) [8]

Fig. 14. Water garden above the parking lot. The Design Museum. Barcelona (2022) [8]

Fig. 15. Operational green roof. Eco-hotel. Normandy (2012) [8]

Fig. 16. Club green roof of the Skolkovo Business School. Moscow (2011) [8]

Fig. 17. Private terraces of the ”Vertical Forest" Architect Stefano Bori. Milan (2016) [8]

The benefits of using green roofing (Table 5) are as follows [10]:

- possibility of a dramatic increase in the energy efficiency of buildings leading to a reduction in energy costs and optimization of resource use;
- effective measures in order to combat the urban "heat island" by reducing the temperature in the urban environment;
- noise reduction by means of vegetation in order to absorb sound waves;
- rainwater capture, thereby reducing the burden on the urban sanitation system;
- improving air quality and reducing environmental pollution;
- extending the service life of roofs and reducing the need for them to be replaced;
- creating additional green recreational spaces for public use;
- restoring the biodiversity of urban ecosystems and providing a natural habitat for different animal species [12].

Table 5

Positive effects of using green roofing [11]

Category	Benefit	Owners / investors	Users / tenants	Local community
Economic	Improving the nergy efficiency of a building	√√	√√	√
	Reducing the load on heating, ventilation, and air conditioning systems	√√	√√	○
	Increase in the value of real estate	√√	√	○
	Increasing the service life of a roofing	√√	√√	√
	Improving the efficiency of using solar panels	√√	√√	√
	Reducing the cost of creating and maintaining drainage systems and storm sewers	√√	√√	○
Architectural and urban planning	Increasing the aesthetic appeal of urban development, improving the physical appearance of buildings and structures	√√	√√	√√
	Improving building energy efficiency and environmental friendliness evaluates	√√	√√	√
Environmental	Reducing the „heat island“ effect	○	√√	√√
	Improving the air quality	○	√√	√√
	Carbon sequestration (greenhouse gases)	○	√√	√√
	Stormwater runoff accumulation	○	√√	√√
	Reduction of stormwawter runoff peaks	○	√√	√√
	Reducing urban noise levels	○	√√	√√
	Recreating the natural environment	○	○	√√
	Conservation of biodiversity in urban areas	○	○	√√
Social	Creating new jobs	√√	○	√√
	Creating new functional and public spaces	√√	√√	√√
Social	Citizen involvement in urban/rural development	√	√√	√√
	Opportunity for food production	√	√√	√√

√√ — a great effect
√ — a medium effect
○ — a zero or an almost zero effect

Discussion and Conclusion. The introduction of green roof standards is not merely a new element in construction, but a whole different approach to building lifecycle management. This approach includes not only the construction and equipping of facilities, but also ensuring environmental sustainability, energy conservation, and improving living standards. However, introducing green roofs into the construction sector is lengthy and ambiguous and also requires time to be optimized and adapted.

The successful and common use of green roofs requires support at the legislative level, as well as a change in the minds of those involved in the construction process who are willing to adapt to new standards and implement environmentally sustainable solutions. From the standpoint of urban planning, the concept of green roofing is an indisputable benefit for developers since it brings together improvement of physical appearance as well as environmental parameters of buildings with effective technologies in order to reduce energy consumption and conserve resources. Therefore green roofing is becoming an innovative solution combining functionality and aesthetics as well as environmental consciousness. Standards and regulation in this context have a key role to play in ensuring sustainability and effectiveness of such systems, making them an essential step to designing more environmentally friendly cities that contribute to public well-being.

References

1. Weiler S, Scholz-Barth K *Green Roof Systems: A Guide to the Planning, Design and Construction of Building Over Structure*. NJ: John Wiley & Sons, Inc.; 2009. 320 p. https://doi.org/10.3368/lj.29.1.92

2. Oberdorfer E, Lundholm JT, Bass B, Coffman R Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *BioScience*. 2007; 57:823–833. https://doi.org/10.1641/B571005

3. Osmundson T *Roof Gardeus: History, Design and Construction.* New York: W.W. Norton; 1999. 318 p.

4. *Classification System Proposed for Green Roofs.* URL: https://phys.org/news/2013-10-classification-green-roofs.html (accessed: 21.04.2025).

5. Kireeva TV *Architectural and Landscape Design of a Green Exploited Roof.* Moscow: TRIUMPH; 2019. 112 p. (In Russ.)

6. Kireeva TV History of the Creation of the "Hanging Gardens" of the Rockefeller Center. *Forest Bulletin.* 2018;22(4):18–26. (In Russ.) URL: https://les-vest.mf.bmstu.ru/les_vest/2018/4_2018/18-26.pdf (accessed: 21.04.2025).

7. Kireeva TV Hanging Gardens of London at the Beginning of the Twentieth Century. *Modern High-Tech.* 2018;5:91–66. (In Russ.) URL: https://top-technologies.ru/ru/article/view?id=36997 (accessed: 21.04.2025).

8. Kireeva TV Hundertwasser's Green Roofs. *Proceedings of the XVIII Scientific and Practical Conference "Landscape Architecture"*. Nizhny Novgorod: Nizhny Novgorod State University of Architecture and Civil Engineering; 2020. pp. 44-47. (In Russ.)

9. Titova NP *Roof Gardens.* Moscow: OLMA-PRESS Grand; 2002.112 p.(In Russ.)

10. Bochkovskaya MA *A High-Quality "Green Roof" Can Increase the Value of a Property by 6-15%.* (In Russ.) URL: https://erzrf.ru/publikacii/kachestvennaya-zelenaya-krysha-mozhet-uvelichit-stoimost-obyekta-nedvizhimosti-na-615 (accessed: 21.04.2025).

11. Le Corbusier. *Architect of the Twentieth Century.* Moscow: Progress; 1977. 303 p.(In Russ.)

12. Gorokhov VA *Green Nature of the City.* Moscow: Architecture-C; 2005. 528 p.(In Russ.)

About the Authors:

Svetlana G. Sheina, Dr.Sci. (Eng.), Professor, Head of the Department of Urban Construction and Agriculture, Don State Technical University (162 Sotsialisticheskaya Str., Rostov-on-Don, 344003, Russian Federation) ScopusID, ORCID, rgsu-gsh@mail.ru

Ruslan V. Balashev, Master's student of the Department of Urban Construction and Agriculture at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), ruslanbalashev33@gmail.com

Roman D. Shakhiev, Master's student of the Department of Urban Construction and Agriculture at the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 344003, Russian Federation), romanshahiev@yandex.ru

W. Shixiao , PhD student in Civil Engineering at Shandong Jiaotong University (People's Republic of China, Shandong Province, Jinan,), ORCID, 1264950586@qq.com

Claimed authorship:

RV Balashev: formation of the basic concept, aims of the study, preparation of the manuscript, formation of the conclusions;

SG Sheina: scientific supervision, analysis of the research results, revision of the manuscript, correction of the conclusions;

RD Shakhiev: formation of an additional concept, preparation of the manuscript and formation of the conclusions;

W Shixiao: preparation of the manuscript.

Conflict of interest: the authors declare no conflict of interest.

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

Об авторах:

Светлана Георгиевна Шеина, доктор технических наук, профессор, заведующая кафедрой городского строительства и хозяйства Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, ул. Социалистическая, 162), ScopusID, ORCID, rgsu-gsh@mail.ru

Балашев Руслан Вадимович, магистрант кафедры городского строительства и хозяйства Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, ул. Социалистическая, 162), ruslanbalashev33@gmail.com

Шахиев Роман Джабарович, магистрант кафедры городского строительства и хозяйства Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, ул. Социалистическая, 162), romanshahiev@yandex.ru

Шисяо У, аспирант по направлению «Civil Engineering» Шаньдунского транспортного университета (Китайская народная республика, провинция Шаньдун, г. Цзинань,), ORCID, 1264950586@qq.com

Заявленный вклад авторов:

Р.В. Балашев: формирование основной концепции, цели и задачи исследования, подготовка текста, формирование выводов;

С.Г. Шеина: научное руководство, анализ результатов исследований, доработка текста, корректировка выводов;

Р.Д. Шахиев: формирование дополнительной концепции, подготовка текста и формирование выводов;

У Шисяо: подготовка текста.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 22.04.2025
Reviewed / Поступила после рецензирования 14.05.2025
Accepted / Принята к публикации 28.05.2025