Строительные материалы и изделия
Construction Materials and Products

journal homepage: https://bstu-journals.ru

ISSN 2618-7183

DOI: 10.58224/2618-7183-2024-7-1-4

Calculation of monolithic buildings structures taking into account the nonlinear operation of reinforced concrete

Ksenofontova T.K. *[1], Mareeva O.V. [1], Verkhoglyadova A.S. [1]

[1] Russian State Agrarian University-Moscow Timiryazev Agricultural Academy, Russia

Abstract. Buildings and structures made of reinforced concrete are currently designed, as a rule, under the assumption of linear work of the material. However, in accordance with the requirements of modern standards, it is necessary to take into account the nonlinear operation of concrete and reinforcement in calculations. In the research presented in the article, using the example of a building with a wall structural system, the influence of taking into account the physical nonlinearity of reinforced concrete on the operation of its structures was considered. It was received that due to the nonlinear operation, there is a prospect of a possible reduction in the calculated forces affecting the strength and width of crack opening, and, consequently, the reinforcement consumption. In addition, when taking into account the work of reinforcement in the zone of yield stresses in ceilings and walls, local plastic areas may form that require reinforcement, which are not fixed in linear calculations.
The calculations were performed in the LIRA-CAD 2021 software package. The results of the calculations showed that taking into account the nonlinear operation of reinforced concrete when considering the floors of a building allows reducing the design efforts compared to calculations performed in a linear formulation by about (3 - 30)%, and when calculating walls, on the contrary, taking into account the physical nonlinearity of reinforced concrete, internal forces increase in some cases more more than twice. Taking into account the physical nonlinearity of reinforced concrete work also leads to a more correct assessment of floor deflections.
Keywords: building, non-linear work of reinforced concrete, redistribution of forces in floors and walls of panel buildings, reinforcement of floor slabs and walls, crack opening width

Please cite this article as: Ksenofontova T.K., Mareeva O.V., Verkhoglyadova A.S. Calculation of monolithic buildings structures taking into account the nonlinear operation of reinforced concrete. Construction Materials and Products. 2024. 7 (1). 4. DOI: 10.58224/2618-7183-2024-7-1-4

1. INTRODUCTION

In modern construction, the construction of buildings and structures from monolithic reinforced concrete is widely used. One of the most frequently used structures of monolithic buildings are buildings with wall structural system [1, 2], in which the internal walls are load-bearing and absorb the act-

*Corresponding author E-mail: tksenofontova@rgau-msha.ru, Ksentanya@yandex.ru

Received November 6, 2023; Received in revised form January 8, 2024; Accepted February 10, 2024

ing vertical loads from the pavement and slabs, as well as wind loads and loads of other types. Nowadays, the design of buildings, as a rule, is carried out using modern software systems by means of the finite element method [3-5]. In this case, the calculation of structures in the design is performed in a linear formulation, and the purpose of the calculation is mainly the selection of reinforcement while ensuring strength and allowable crack opening width [6]. Checking the deflections of slabs with this approach gives significantly underestimated values of design values, which require correction that takes into account the nonlinear work of reinforced concrete. The question of the necessity to take into account the nonlinear operation of concrete and reinforcement in the design of buildings and structures has been considered by various scientists [7-12]. The calculation of buildings taking into account the nonlinear operation of reinforced concrete is especially important when checking them for progressive collapse [13, 14]. However, in practice, the calculation of structural elements of buildings taking into account nonlinear operation, as a rule, is not performed because it is considered that the influence of this factor on the design results is not very great.

2. METHODS AND MATERIALS

The aim of the research was to evaluate the influence on the calculation results of taking into account the nonlinear work of reinforced concrete – on internal forces, reinforcement, crack opening width in slabs and walls of buildings with a wall structural system, as well as deflections and absolute displacements in floors. Therefore, the task of this study was to determine the degree of necessity to take this factor into account in the design. When selecting the object of research, it was taken into account that buildings can be of different storeys, therefore, medium storey buildings were selected for research on the assessment of the influence of nonlinear performance of reinforced concrete on the performance of slabs and walls.

Calculation of buildings as spatial structures is possible only with the use of modern program complexes such as ANSIS, SCAD, STARK ES and others. One of the most widely used in design is the LIRA-SAPR complex, which realizes the possibility of calculating structures both in linear position and taking into account physical, geometric and structural nonlinearity. LIRA-SAPR reflects the requirements of current design standards adopted in Russia. Therefore, LIRA-SAPR was adopted as a tool for research of the influence of nonlinear reinforced concrete performance on the results of calculation of slabs and walls of buildings with a wall structural system.

Three-storeyed monolithic reinforced concrete buildings with the same length of 48 m and different widths of 9 m, 12 m and 15 m were taken as an object of research. The layout of rooms and bearing walls inside the buildings was assumed to be the same. Calculation of buildings and investigation of their operation were carried out using the program complex PC "LIRA-SAPR 2021". For modeling of load-bearing structures finite element shells with dimensions of 0.5 x 0.5 m were used. Fig. 1 shows the finite element model of the buildings under study, as well as a conditional section of the model on the second floor.

a *b*

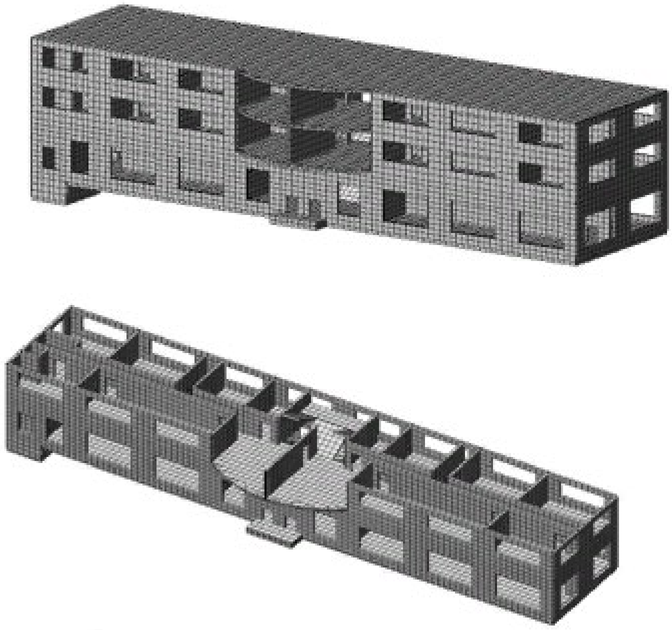

Fig. 1. A finite element model of the buildings under study with a wall structural system (a) and a section of the model on the second floor (b).

The concrete class B25, working longitudinal reinforcement of class A500C, transverse and structural reinforcement of class A240 were adopted for the building structures. The thickness of floor slabs and pavement and walls was 200 mm, the thickness of the foundation slab was 600 mm. Under the foundation slab a multilayer soil base was envisaged, the model of which was adopted according to P.L. Pasternak with two bedding coefficients, the magnitude of which and their distribution over the area of the foundation slab were calculated directly in the PC "LIRA-SAPR 2021".

The calculation took into account the constant loads from the own weight of the load-bearing structures, floors on the slabs, roofing on the floor slab, and the weight of the pavement on the foundation slab. The temporary loads taken into account in the calculations were taken according to the standards depending on the purpose of the premises, and the snow load was taken into account on the pavement. In addition, the wind load was taken into account for different directions of its influence.

The calculation of the building structures was carried out in two stages. First, linear calculation was performed, the purpose of which was to select reinforcement in slabs and walls. Then, the type of finite elements was changed for load-bearing structures in order to be able to perform their calculation in a nonlinear formulation. The laws of nonlinear deformation of concrete and reinforcement were adopted in accordance with the dependencies according to [5], shown in Fig. 2 and implemented in PC "LIRA-SAPR 2021".

a *b*

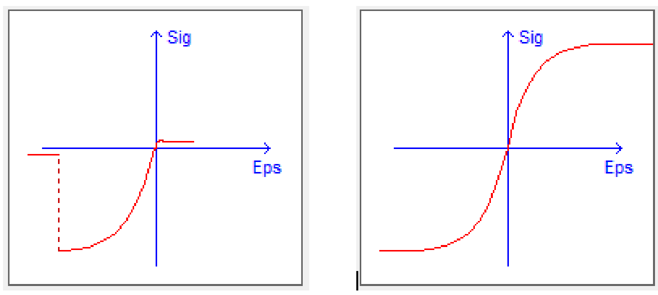

Fig. 2. Deformation diagrams σ–ε for concrete (a) and reinforcement (b).

3. RESULTS AND DISCUSSION

As a result of the calculations, the distributions of bending moments in slabs and walls were obtained in a linear formulation and taking into account physical nonlinearity. When taking into account the physical nonlinearity of reinforced concrete in the floor slabs of buildings, the displacement distribution fields and crack opening widths were obtained. Table 1 shows the comparison of bending moments in spans and at supports in the second floor slabs along the building - M_x and across the building - M_y. In the column "Type of calculation" the following designations are introduced: the letter "A" denotes the results of calculations performed in a linear formulation, and the letter "B" denotes the results of calculations performed taking into account the physical nonlinearity of reinforced concrete. As it can be seen from Table 1, accounting for the physical nonlinearity of reinforced concrete performance has a significant effect on the internal forces in floor slabs of panelized buildings, which ranges from 3% to 30%.

Table 1. Bending moments in the 2nd floor floor slab.

Type of calculation	Building 48 x 9 m		Building 48 x 12 m		Building 48 x 15 m	
	support	span	support	span	support	span
	Bending moments M_x, (kN*m)					
A	–12.9	12.3	–19.1	15.5	–23.8	19.1
B	–8.76	11.3	–13.0	15.0	–17.3	18.5
%	32.1	8.1	31.9	3.2	27.3	3.1
	Bending moments M_y, (kN*m)					
A	–16.9	8.93	–19.8	12.5	–23.1	17.7
B	–14.8	7.78	–16.6	10.6	–20.8	14.9
%	12.4	13.2	16.2	15.2	10.0	15.8

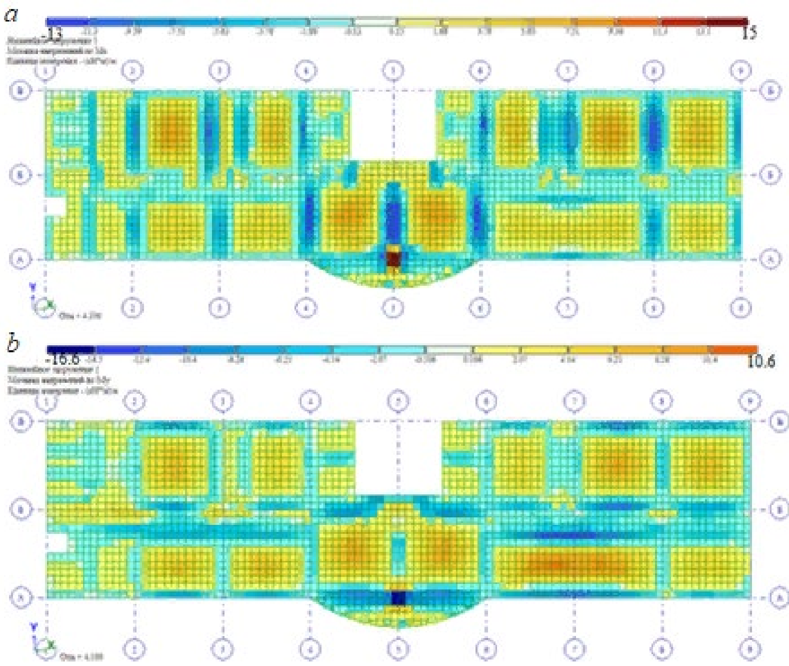

Fig. 3. Mosaics of the distribution of bending moments in the floor slab of a building with dimensions of 48 x 12 m, taking into account the physical nonlinearity of reinforced concrete: *a* – moments M_x along the building; *b* –moments M_y in the transverse direction of the building.

Fig. 3 shows the mosaics of bending moment distributions in (kN*m) taking into account the physical nonlinearity of reinforced concrete for a building with dimensions 48 x 12 m. The results of bending moment values, shown in Fig. 3, show that the areas of the floor slab in the central part were the most loaded, where there is a semicircular balcony, extending beyond the coordination axis A and creating additional load for the part of the slab between the axes 4-6 of the floor within one span across the width of the building.

As calculations have shown, cracks are formed in the floor slabs of buildings, but the width of their opening and taking into account the physical nonlinearity of reinforced concrete, and without taking into account this factor was within the permissible values. Fig. 4 shows mosaics of the crack opening width on the upper and lower surfaces of the floor slab of the second floor of the building with the dimensions in plan 48 x 12 m. The value of crack opening in the slabs according to the calculation was about 0.2 mm, which is less than the permissible value determined by the norms from the condition of preservation of reinforcement from corrosion under continuous action of loads, equal to 0.3 mm.

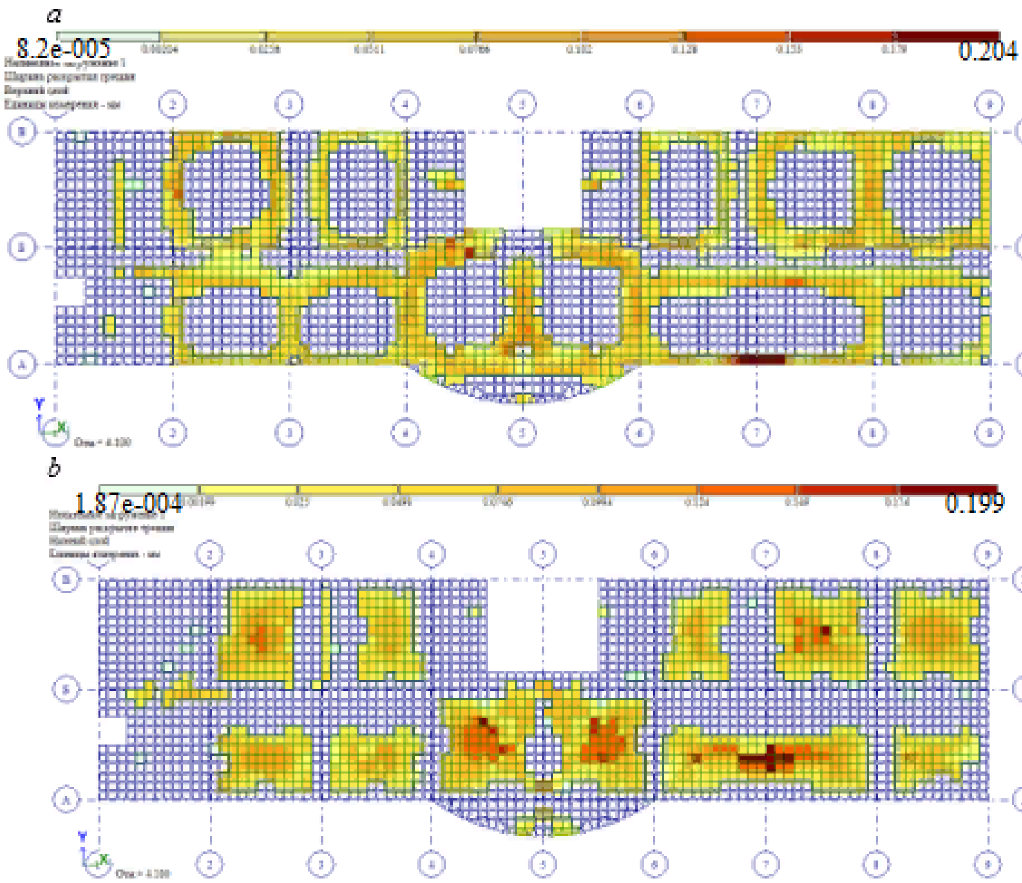

Fig. 4. Mosaics of the distribution of the crack opening width in the floor slab of a building with dimensions of 48 x 12 m, taking into account the physical nonlinearity of reinforced concrete: *a* – on the upper surface of the floor slab; *b* – on the lower surface of the floor slab.

Fig. 5 shows a diagram comparing the displacements in the floor slabs of the second floor of buildings in calculations without taking into account and taking into account the physical nonlinearity of reinforced concrete. It follows from Fig. 5 that without taking into account the physical nonlinearity of concrete and reinforcement, the results of deflections calculation are significantly underestimated.

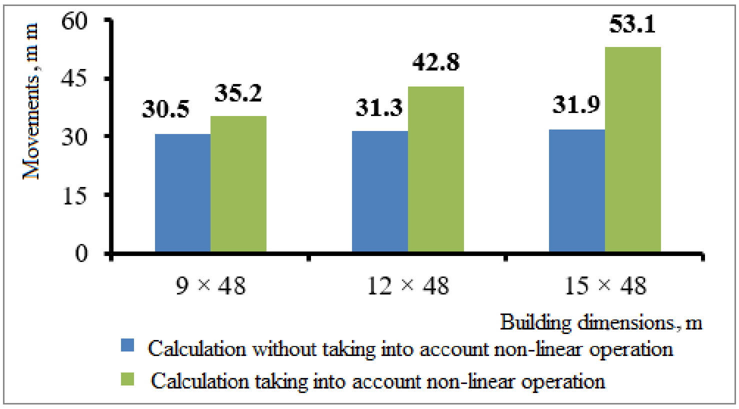

Fig. 5. Maximum vertical movement in the floor slab of the 2nd floor.

For the walls of buildings, a comparison of bending moments in the linear calculation of building structures was also carried out with calculations made taking into account the physical nonlinearity of reinforced concrete performance. Table 2 shows the values of maximum moments M_x along the wall in the horizontal direction and maximum moments M_y in the vertical direction. As it can be seen from Table 2, the values of bending moments in the walls due to taking into account the physical nonlinearity of reinforced concrete work were significantly greater than without taking this factor into account. The presence of cracks in the walls of the investigated panel buildings was not recorded in the calculations.

Table 2. Bending moments in the walls of the 2nd floor along axis 8.

Type of calculation	Building 48 x 9 m		Building 48 x 12 m		Building 48 x 15 m	
	support	span	support	span	support	span
	Bending moments M_x, (kN*m)					
A	–0.398	0.908	–0.465	1.13	–0.537	1.35
B	–0.876	1.51	–0.989	1.98	–1.14	2.48
%	120.1	66.3	113	75.2	112	83.7
	Bending moments M_y, (kN*m)					
A	–0.883	3.38	–1.48	4.39	–1.86	5.34
B	–1.09	4.24	–1.99	5.93	–2.35	7.67
%	23.4	25.4	34.5	35.1	26.3	43.6

As it can be seen from the calculation results, taking into account the physical nonlinearity of reinforced concrete in buildings with a wall structural system leads to a redistribution of forces between slabs and walls compared to calculations performed in a linear formulation. Thus, taking into account the physical nonlinearity of reinforced concrete contributes to the reduction of internal forces in the slabs of buildings on the supports from 10% to 30%, in the spans - from 3% to 16%, and in the walls, on the contrary, there is a significant increase in the values of bending moments in both horizontal and vertical directions. The results of calculations have shown that due to the reduction of bending moments when taking into account the nonlinear operation of reinforced concrete, slabs have reinforcement reserves that can be reduced without damage by about 10-15%. At the same time, in the walls, when taking this factor into account, there is a deficit of reinforcement, which can in turn lead the building to an emergency situation.

The results of calculations also showed that taking into account the physical nonlinearity affects the displacements and deflections of slabs, leads to a significant increase in their design value, which is not taken into account by linear calculations of buildings (Fig. 5). With the increase of the building width the difference in the values of displacements in the slabs when taking into account the nonlinear work of reinforced concrete in comparison with its linear calculation increased sharply and for a building with dimensions of 48 x 15 m amounted to 40% higher values in comparison with the calculation of buildings in a linear setting.

4. CONCLUSION

The results of calculations of the studied structures of buildings with wall structural system have shown that taking into account in calculations the physical nonlinearity of reinforced concrete significantly affects the design results. In this case, there is a redistribution of forces, which leads to a decrease in bending moments in the slabs and an increase in the forces in the walls. Apparently, this is due to the fact that at the initial moment the values of bending moments in slabs are larger in magnitude than in walls, so in slabs plastic deformations in concrete occur earlier, smoothing out the force peaks, and also the formation of cracks occurs, which, as it is known [15], leads to a decrease in the design value of moments in sections with cracks and an increase in moments in sections of the structure where there are no cracks. This is all the more probable in view of the fact that the building calculations have shown that no cracks have formed in the walls.

It was also found that deflections and deformations in buildings should be evaluated only when the physical nonlinearity of reinforced concrete performance is taken into account, otherwise the condition of slabs may be incorrectly evaluated in terms of suitability for normal operation.

It should also be noted that in buildings with a wall structural system, by taking into account in calculations the physical nonlinearity of reinforced concrete operation when reinforcing slabs, it is possible to achieve reinforcement savings of about 10-15%, while walls without taking this factor into account in calculations may be insufficiently reinforced.

REFERENCES

[1] Vilchik N.P. Architecture of buildings. M.: INFRA-M, 2008. 303 p.

[2] Kodysh E.N., Nikitin I.K., Trekin N.N. Design of multi-storey buildings with reinforced concrete frame. M.: ASV Publishing House, 2009. 352 p.

[3] Klyuev S.V., Kashapov N.F., Radaykin O.V., Sabitov L.S., Klyuev A.V., Shchekina N.A. Reliability coefficient for fibreconcrete material. Construction Materials and Products. 2022. 5 (2). P. 51 – 58. https://doi.org/10.58224/2618-7183-2022-5-2-51-58

[4] Gorodetsky A.S., Evzerov I.D. Computer models of structures. Kiev: Publishing House Fact, 2007. 344 p.

[5] Gorodetsky A.S., Barabash M.S., Sidorov V.N. Computer modeling in problems of structural mechanics. M.: ASV Publishing House, 2016. 337 p.

[6] Novoselov O.G., Sabitov L.S., Sibgatullin K.E., Sibgatullin E.S., Klyuev A.S., Klyuev S.V., Shorstova E.S. Method for calculating the strength of massive structural elements in the general case of their stress-strain state (kinematic method). Construction Materials and Products. 2023. 6. (3). P. 5 – 17. https://doi.org/10.58224/2618-7183-2023-6-3-5-17

[7] Klovanich S.F., Bezushko D.I. Finite element method in nonlinear calculations of spatial reinforced concrete structures. Odessa: ONMU Publishing House, 2009. 89 p.

[8] Kenzhimbetov T.A., Varlamova T.V. Design of high-rise buildings in earthquake-prone areas with high wind loads. Design and construction: Collection of scientific papers of the 3rd International Scientific and Practical Conference of Young Scientists, Postgraduates, Masters and Bachelors. Moscow: Southwest State University, Moscow State Engineering University, 2019. P. 219 – 222.

[9] Gamayunov V.P., Esin A.I., Isaev A.A. On the issue of ensuring the reliability of reconstructed buildings. Resource and energy efficient technologies in the construction complex of the regio. 2014. 4. P. 228 – 232

[10] Karpenko N.I., Sokolov B.S., Radaykin O.V. On the determination of deformations of bent reinforced concrete elements using deformation diagrams of concrete and reinforcement. Construction and reconstruction. Collection of scientific papers. Orel: Oryol State University named after I.S. Turgenev, 2016. 5. P. 19 – 25.

[11] Ksenofontova T.K. Engineering structures (3rd edition revised and supplemented). Publisher MSUEE, 2011. 143 p.

[12] Varlamova T.V., Ksenofontova T.K., Verkhoglyadova A.S., Mareeva O.V. Consideration of dynamic impacts in the design of cantilever structures. Construction Materials and Products. 2022. 5 (6). P. 54 – 63. https://doi.org/10.58224/2618-7183-2022-5-6-54-63

[13] Korenkov P.A. Construction of a computational model taking into account the nonlinear properties of the material in the analysis of the danger of progressive collapse of reinforced concrete frames. Construction and technogenic safety. Collection of scientific papers. M.: Publishing house of KFU named after V.I. Vernadsky. 2013. 28. 33 p.

[14] Klyuev S.V., Shlychkov D.I., Muravyov K.A., Ksenofontova T.K. Optimal design of building structures. International Journal of Advanced Science and Technology. 2020. 29(5). 2577–2583.

[15] Ksenofontova T.K. The method of calculating statically indeterminate reinforced concrete structures, taking into account the redistribution of forces during cracking. Nature management. 2008. № 4. P. 88 – 95.

INFORMATION ABOUT THE AUTHORS

Ksenofontnova T.K., e-mail: tksenofontova@rgau-msha.ru, Ksentanya@yandex.ru, тел. +7 (499) 976 26 43, +7 (916) 856 4851, ORCID ID: 0000-0002-3484-6894, SCOPUS: https://www.scopus.com/authid/detail.uri?authorId=57216621271, Researcher ID: AAE-1703-2022, Google Scholar ID: C-Df4EYAAAAJ, Russian State Agrarian University-Moscow Timiryazev Agricultural Academy, Institute of Land Reclamation, Water Management and Construction named after A.N. Kostyakov; Department of Engineering Structures, Candidate of Engineering Sciences (Ph.D.), Associate Professor

Mareeva O.V. e-mail: o.mareeva@rgau-msha.ru, тел. +7 (499) 976 26 43, +7 (916) 505 60 41, ORCID ID: 0000-0002-7441-2169 Russian State Agrarian University-Moscow Timiryazev Agricultural Academy, Institute of Land Reclamation, Water Management and Construction named after A.N. Kostyakov; Department of Engineering Structures, Candidate of Engineering Sciences (Ph.D.), Associate Professor

Verkhoglyadova A.S., Russian State Agrarian University-Moscow Timiryazev Agricultural Academy, Institute of Land Reclamation, Water Management and Construction named after A.N. Kostyakov; Department of Engineering Structures, Senior Lecturer