CALCULATION OF LARGE-SPAN GLULAM STRUCTURES AS A SOIL BASE-FOUNDATION-ABOVE-GROUND STRUCTURE SYSTEM

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ABSTRACT

The object of research. Long-span glulam arches are widely used as coatings for public and sports buildings. The studies carried out concern double-hinged segmental arches with spans of 60 m and more.

Description of the problem. The study of the peculiarities of the work of arches as a system "soil base – foundation – above-ground structure" is associated with the significant influence of uneven deformations of supports on the stress-strain state of the above-ground structure. A change in the stress-strain state in the structure itself, associated with uneven deformations of the foundations, can lead to a significant decrease up to the complete exhaustion of the bearing capacity

Main scientific results. This article provides an analysis of the change in the stress-strain state of glulam arches when calculating the system "soil base-foundation-above-ground structure". It is noted that non-uniform deformations of supports have the greatest influence on the stress in the support zones of the structure. The range of critical non-uniform subsidence has been determined, which should be limited when calculating and designing the foundations of large-span arches. It has been confirmed that double-hinged glulam arches work well in conditions of uneven subsidence due to the peculiarities of the design scheme.

The results of the studies carried out and the recommendations provided will significantly improve the reliability of large-span structures and require mandatory inclusion in the current practice of calculation and design. In addition, additional requirements for the distance between mine workings for large-span structures should be introduced when performing engineering and geological surveys. This distance should be reduced for a clearer account of the deformability of the foundations for columnar foundations, and the number of workings should be increased.

The area of practical use of the research results. The cross-section of the glulam arches is selected taking into account additional deformations of the supports, making it possible to avoid unpredictable damage to the structure during operation.

Innovative technological product. Glulam arches, the cross-section of which is determined taking into account additional deformations from uneven subsidence of the supports

Scope of application. Glulam arches calculated in this way can be used as covering for public and sports buildings for various purposes.

1. Introduction

1. 1. The object of research

The above studies concern double-hinged glulam arches with a span of 60 m and more. When calculating large-span arches as a system "soil base-foundation-above-ground structure", it was noted that uneven subsidence associated with the possible presence of weak soil layers significantly affect the stress-strain state of the structure.

1. 2. Problem description

Large-span structures, such as arches, frames, trusses, cable-stayed coverings, etc., made of glulam have long been widely used in many countries of the world [1–4], as a covering for public and sports buildings for various purposes. Due to the fact that glulam effectively accumulates the positive properties of wood as a structural material, its use for large-span structures is quite justified.

With the increase in production capabilities, the range of use and application of glulam structures increases, and therefore a number of questions arise for its more rational use. One of the problems of large-span buildings is the uneven subsidence of the supports, which is associated with the heterogeneity of the geological composition of the base (soils) or the presence of layers of weak soils in it.

Taking into account the prevalence of glulam arches, the study of the influence of uneven subsidence of supports on the stress-strain state (SSS) is an urgent scientific task.

1. 3. Suggested solution to the problem

In the countries of the European Union, the United States of America, Japan, China, etc. since the 90s of the last century, the necessity of calculating structures as a system "soil base-foundation-above-ground structure" has been recognized. The normative documents of Ukraine [5] and Europe [6] also declare the need for such calculations, but there are actually no specific instructions on how to carry them out with respect to certain structures. DBN V.2.1-10 [7] limits the maximum deformations of buildings, namely the limiting value of the maximum subsidence and inclination of buildings without reference to the material from which this or that structure is made. In fact, in the main regulatory document on the calculation of foundations and design of foundations, there are no specific restrictions on uneven subsidence of large-span glulam structures. It should be noted that large-span structures generally have their own specificity of foundation structures, which consists in the fact that only free-standing foundations are used. In this case, the calculation of the foundations is carried out for maximum efforts on the edge of the foundations from the calculated limit values of the load, taking into account the worst composition of the soil base according to the results of engineering and geological surveys. The deformations of each foundation are not checked.

It should be noted that in a market economy, the number of exploration wells, at best, is clearly regulated by DBN A.2.1-1 [8] in order to save money. This number of surveys allows for a significant probability of finding layers of soft soils on the construction site, as evidenced by construction experience. And if, with insignificant spans, this factor can really be leveled out of the foundation structure or with sufficient rigidity of the above-ground structure, then for large-span structures this can lead to a significant change in the stress-strain state of the structure.

The study of the influence of uneven subsidence of supports on the stress-strain state of overground wooden structures was carried out only for glulam arches, which is the subject of work [9].

The aim of this research is to numerically study the effect of uneven subsidence of supports on the stress-strain state of glulam arches.

2. Materials and methods

The object of research was a building with large-span glulam arches. The building is single-span, with dimensions in the plan 60×60 m, the spacing of the supporting structures is 3 m (**Fig. 1**). According to the structural scheme, the arches are double-hinged, that is, they have a hinge connection in the support nodes. There are three tie blocks along the length of the building (two at the ends and one in the middle of the building). The foundations are taken columnar, shallow, made of monolithic reinforced concrete.

The engineering-geological structure of the construction site is represented by fine and medium-sized sands corresponding to the engineering-geological structure for the city of Kyiv.

Modeling was carried out in the LIRA-SAPR software package. When modeling the arch with flat FE No. 44, the physical and mechanical characteristics of wood of strength class GL 28h were set: modulus of elasticity of wood along the fibers $E_1=E_{0,\text{mean}}$=12,600 MPa; modulus of elasticity of wood across the fibers $E_2=E_{90,\text{mean}}$=420 MPa; shear modulus $G=G_{\text{mean}}$=780 MPa, Poisson's ratio along the fibers $\mu_{90,0}$=0.48; Poisson's ratio across the fibers $\mu_{90,0}$=0.018.

The size of the cross-section of the arches is 110×25 cm. To create hinged support nodes, metal parts have been modeled, which provide free rotation of the nodes. The design load is assumed to be uniformly distributed along the length of the arch.

According to the calculation of base deformations according to the method [7] in the geological conditions of the construction site, the displacements were S_1=12.6 mm. Considering that the soil of the construction site has a heterogeneous composition, uniform subsidence of the foundations is unlikely.

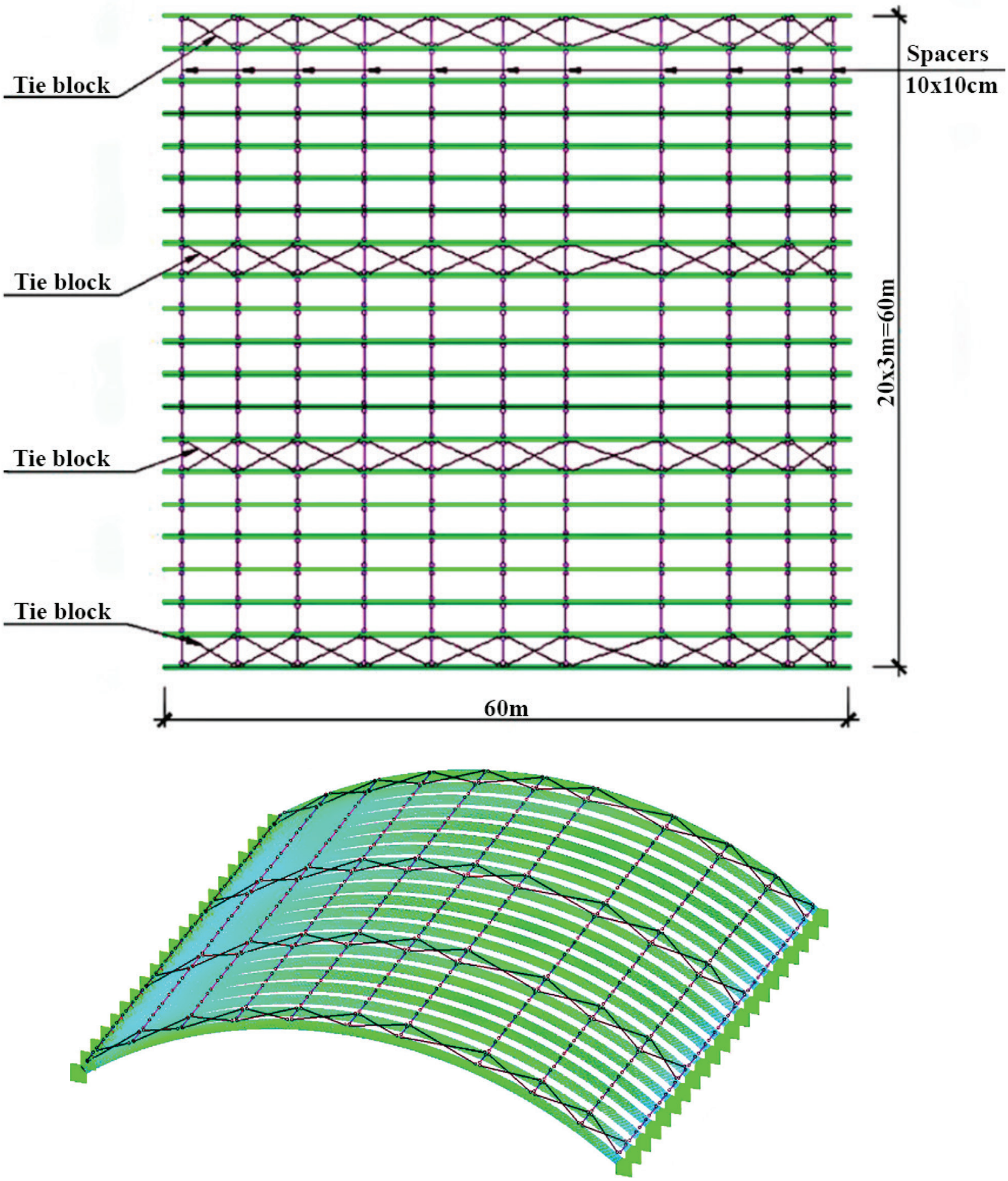

Fig. 1. General view of the building adopted for numerical research

To study this phenomenon, numerous studies were carried out using the FEM, taking into account the displacement of one of the supports of the predicted subsidence, determined by the method [7].

The stress in the sections of the arch arising from uneven deformations should be less than the design resistance of the wood and ensure the normal operation of the structures.

Numerous studies have been carried out for an ordinary arch, not related to tie blocks. At the first stage, the calculation is carried out with a uniform subsidence of the supports. The calculation results are shown in **Fig. 2.**

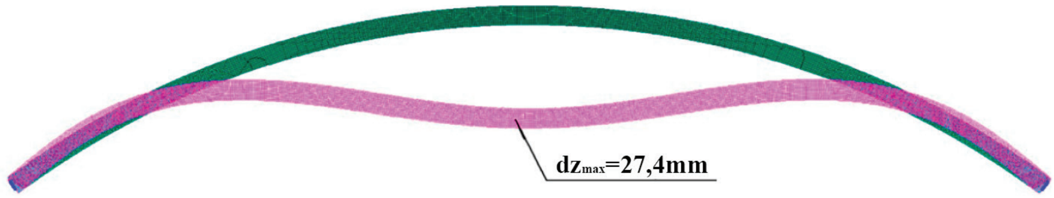

Fig. 2. The original and deformed schemes with uniform subsidence of the supports

To study the stress-strain state in the sections of glulam arches with uneven subsidence, a layer of peat loam with a thickness of 5.2 m with a modulus of deformation E=2 MPa was introduced under the right support into the soil base, under the left support the soil base remained unchanged. According to the calculation of the deformations of the right support under the conditions of a new geological structure, the displacements were S_2=30.1 mm, and the difference in displacements between the supports $D=S_2-S_1$=17.5 mm.

In the design scheme, the difference in displacements is implemented by displacing the nodes of the right support by a predetermined amount. The results of calculating glulam arches with uneven subsidence of supports are shown in **Fig. 3.**

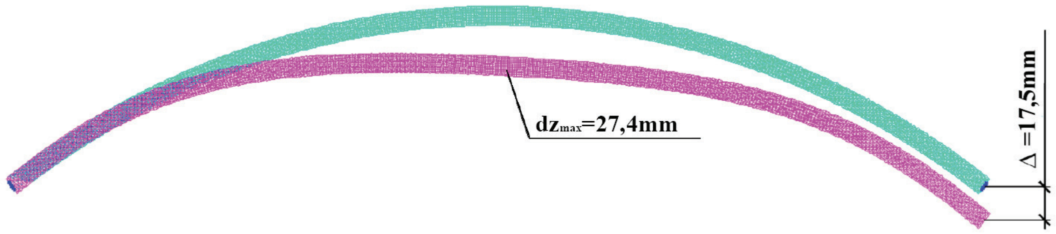

Fig. 3. The original and deformed schemes in case of uneven subsidence of the supports

In engineering practice, to determine the subsidence of columnar foundations, methods are used based on the design diagrams of a linearly deformed half-space, which have some simplifications and significantly idealize the work of the soil foundation.

Such an engineering approach does not allow taking into account the heterogeneity of the soil base, the nonlinearity of the development of deformations, the development of subsidence properties and other geological phenomena. According to clause 8.4.1 DBN V.2.1-10 [7], the base model should be specified by spatial FEs with appropriate physical and mechanical characteristics.

To check the operation of load-bearing structures in the conditions of a heterogeneous composition of the base, a spatial calculation of the building on a multilayer soil massif was carried out as a system "soil base-foundation-above-ground structure" using the LIRA-SAPR software, taking into account the instructions [10, 11]. The design scheme is shown in **Fig. 4.**

The soil massif is made of physically non-linear FE soil (No. 271–273), which has dimensions in terms of 110×110 m, depth – 20 m. The lower edge is fixed by all linear displacements, vertical – from all horizontal X and Y, respectively. Array nodes, other than those in contact with foundations, are secured against angular displacements. Triangulation of the array was carried out considering the nodes of the foundations to ensure their joint work. The maximum pitch of the FE nodes within the building spot is 0.5 and 1.0 m outside it. The Drucker-Prager criterion was chosen as a condition for shear strength [11].

To simulate preliminary stresses in the soil mass due to its own weight of the soil, as well as to take into account the construction sequence, the PC LIRA-SAPR 2019 module "Installation Plus" was used.

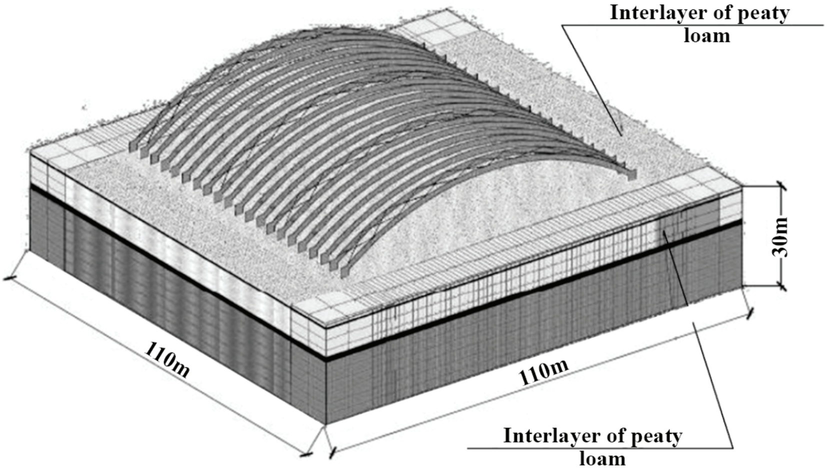

Fig. 4. Finite-element model of a building with a volumetric multilayer soil mass

According to the calculation of glulam arches on a multilayer soil massif, the deformations of the left support were S_1=15.2 mm, the right support S_2=30.5 mm, and the difference in displacement between the supports $D=S_2-S_1$=15.3 mm. The calculation results are shown in **Fig. 5.**

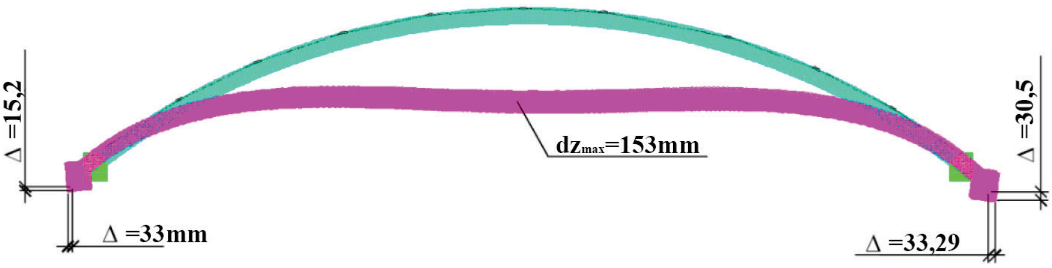

Fig. 5. The original and deformed schemes in the spatial calculation with a multilayer soil massif (FE of soils are conventionally not shown)

3. Research results

As a result of the numerical study, the limiting absolute difference in the settlement of the supports, at which the bearing capacity of the glulam arch is exhausted, is determined, the relationship between the displacements of the supports and the stresses is shown. The research results are shown in **Table 1.**

Table 1

Comparative analysis of the influence of uneven subsidence of supports on stress in laminated wood arches

Calculation charac-teristic	The difference in the seubsidenceof the supports, mm	Support node stress, MPa				Ridge knot stress, MPa	
		σ_x		σ_y		σ_x	σ_y
		left support	right support	left support	right support		
Uniform subsidence of supports	0	4.45	4,47	0.066	0.06	2.51	0.04
Uneven subsidence of supports (determined according to GOST)	17.5	4.17–6.3 %	4.75–5.9 %	0.027–59 %	0.12–50 %	1.17–53 %	0.015–60 %
Uneven subsidence with multi-layer soil mass	30.5	4.52–1.55 %	10.2–56 %	1.07–93 %	2.31–97 %	2.0–20.3 %	0.01–75 %

The difference in settlement between the supports, taking into account the weak soil layer, determined by the method [7] leads to a slight increase in stresses, namely: an increase in displacements by 1.4 times; compressive stress along the fibers (σ_x) in the support zone grows up to 6 %, and in the ridge zone it is redistributed downward; the stress across the fibers (σ_y) in the support zone grows up to 50 %.

The difference in the settlement between the supports, taking into account the weak soil layer using a voluminous soil massif, leads to: an increase in displacements by 2.5 times; the compression stress along the fibers (σ_x) in the support zone grows 1.7 times; compressive stress along the fibers (σ_x) in the ridge zone grows up to 56 %; compression stresses across the fibers (σ_y) in the support zone increase up to 97 %; compression stresses across the fibers (σ_y) in the ridge zone increase up to 20.3 %.

A significant difference in the values of the forces is explained by the appearance of a displacement of one of the supports relative to the other, due to which the geometric axis of the structure changes. This, in turn, changes the redistribution of efforts along the length of the arch in a larger direction, and can lead to the exhaustion of the bearing capacity of the section of the structural element. So, the calculation of such structures according to the "classical scheme", without taking into account the displacement of the supports, gives a large error that cannot be leveled by safety factors.

A feature of this study is the simulation of the displacement of the supports using a volumetric soil massif, which maximally reflects the work of a real structure. The values of individual stresses in the support zones are determined significantly different from the values according to [12], which are explained by the need to clarify the normative calculation methods, taking into account specific design solutions.

4. Discussion

The studies carried out concerned double-hinged glulam arches with a span of 60 m and showed the need to improve the calculation methodology for such structures as the "soil base-foundation-above-ground structure" system. It should be noted that the results obtained are a fundamentally new direction in the comprehensive analysis of the operation of large-span structures. Arched structures of two- and three-hinged arches of various spans, as well as other types of large-span structures, taking into account different soil conditions, require separate studies. Carrying out such global studies of large-area structures such as the "soil base-foundation-above-ground structure" system will allow developing new recommendations for their design, significantly increasing their reliability and safe operation.

Thanks to more accurate modeling of the design scheme, taking into account the uneven deformability of the soil base, it is possible to determine the forces that will approach the real work of the structure. This approach to the calculation is very important for large-span structures with a relatively small cross-section.

A feature of this calculation method is the ability to simulate a soil base of any complexity and perform the calculation promptly, in contrast to manual calculation, which is more simplified. There are no boundary conditions and restrictions for the design of structures, except for the capabilities of the design software package.

The studies carried out concerned only double-hinged glulam arches with a span of 60 m, respectively, the results and practical recommendations are given only for these types of arches.

These studies should be continued in the direction of studying all types of large-span structures of various spans, with different soil conditions and design schemes.

5. Conclusions

1. The fundamental difference between the calculations is the appearance of tensile stresses along the fibers in both zones, significantly affects the bearing capacity of wooden structures, given their strong anisotropy.

2. It is found that when using a volumetric multilayer array, the maximum stresses increase significantly, which is explained by taking into account the work of a volumetric multilayer soil base, affects the change in the stress-strain state of the "soil base-foundation-above-ground structure" system.

3. Double-hinged glulam arches work well in conditions of uneven subsidence due to the design scheme, which makes their use one of the best building solutions in the conditions under

consideration. The permissible difference in the settlement of the supports of the arches under study is approximately in the range of 10–20 mm.

4. The design of the load-bearing frames of buildings with columnar foundations should be carried out on the basis of the spatial calculation of the "soil base-foundation-above-ground structure" system;

5. The distance between mine workings for large-span frames should be reduced for a clearer account of the deformability of the foundations for columnar foundations, and the number of workings should be increased. This issue requires additional research.

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