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International Journal for Computational Civil and Structural Engineering

(Международный журнал по расчету гражданских и строительных конструкций)

Международный научный журнал “International Journal for Computational Civil and Structural Engineering (Международный журнал по расчету гражданских и строительных конструкций)” (IJCCSE) является ведущим научным периодическим изданием по направлению «Инженерные и технические науки», издаваемым, начиная с 1999 года (ISSN 2588-0195 (Online); ISSN 2587-9618 (Print) Continues ISSN 1524-5845). В журнале на высоком научно-техническом уровне рассматриваются проблемы численного и компьютерного моделирования в строительстве, актуальные вопросы разработки, исследования, развития, верификации, апробации и приложений численных, численно-аналитических методов, программно-алгоритмического обеспечения и выполнения автоматизированного проектирования, мониторинга и комплексного наукоемкого расчетно-теоретического и экспериментального обоснования напряженно-деформированного (и иного) состояния, прочности, устойчивости, надежности и безопасности ответственных объектов гражданского и промышленного строительства, энергетики, машиностроения, транспорта, биотехнологий и других высокотехнологичных отраслей.

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Автор имеет возможность следить за продвижением статьи в редакции журнала в личном кабинете Open Journal Systems и получать соответствующие уведомления по электронной почте.

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В ноябре 2020 года журнал начал индексироваться в международной базе Scopus.

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СОДЕРЖАНИЕ

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NUMERICAL SOLUTION OF THE PROBLEM OF ISOTROPIC PLATE ANALYSIS WITH THE USE OF B-SPLINE DISCRETE-CONTINUAL FINITE ELEMENT METHOD

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Abstract: Numerical solution of the problem of isotropic plate analysis with the use of B-spline discrete-continual finite element method (specific version of wavelet-based discrete-continual finite element method) is under consideration in the distinctive paper. The original operational continual and discrete-continual formulations of the problem are given, some actual aspects of construction of normalized basis functions of a B-spline are considered, the corresponding local constructions for an arbitrary discrete-continual finite element are described, some information about the numerical implementation and an example of analysis are presented.

Keywords: wavelet-based discrete-continual finite element method, B-spline discrete-continual finite element method, discrete-continual finite element method, finite element method, B-spline, numerical solution, isotropic plate, plate analysis

ЧИСЛЕННОЕ РЕШЕНИЕ ЗАДАЧИ О ПОПЕРЕЧНОМ ИЗГИБЕ ИЗОТРОПНОЙ ПЛАСТИНЫ НА ОСНОВЕ ВЕЙВЛЕТ-РЕАЛИЗАЦИИ ДИСКРЕТНО-КОНТИНУАЛЬНОГО МЕТОДА КОНЕЧНЫХ ЭЛЕМЕНТОВ С ИСПОЛЬЗОВАНИЕМ B-СПЛАЙНОВ

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Аннотация: В настоящей статье рассматривается численное решение задачи о поперечном изгибе изотропной пластины на основе вейвлет-реализации дискретно-континуального метода конечных элементов с использованием B-сплайнов. Приведены исходные операторные континуальная и дискретно-континуальная постановки задачи, рассмотрены некоторые актуальные вопросы построения нормализованных базисных функций B-сплайна, описаны соответствующие локальные построения для произвольного дискретно-континуального конечного элемента, представлены некоторые сведения о численной реализации и пример расчета.

Ключевые слова: вейвлет-реализация метода конечных элементов, дискретно-континуальный метод конечных элементов, метод конечных элементов, B-сплайны, численное решение, изотропная пластина, изгиб изотропной пластины

INTRODUCTION

As is known [1], the B-spline in a given simple knot sequence can be constructed by employing piecewise polynomials between the knots and joining them together at the knots [1, 2].

For instance, compared with commonly used Daubechies wavelets [3-7] B-spline wavelet on interval (BSWI) has explicit expressions, facilitating the calculation of coefficient integration and differentiation [1, 2]. Besides, the multiresolution and localization properties of BSWI can also supply some superiority for engineering structural analysis [1, 2]. The early applications of spline can be found in papers of H. Antes [8], J.G. Han [9, 10, 26], Y. Huang [9, 10], W.X. Ren [9, 10]. The spline wavelet finite element method was further developed in papers of D.P. Chen [27], X.F. Chen [11, 12, 14-17, 22, 23, 25], H.B. Dong [22], J.G. Han [24], Y.M. He [16], Z.H. He [17], Z.J. He [11, 12, 14-16, 22, 23, 25], Y. Huang [24, 26], Z.S. Jiang [21], B. Li [12, 14, 16, 22], M. Liang [18, 20], J.Q. Long [19], G. Ma [19], T. Matsumoto [19, 21], S.T. Mau [29], H.H. Miao [14], Q,M. Mo [17], T.H.H. Pian [27-29], K.Y. Qi [22], W.X. Ren [24, 26], K. Sumihara [28], P. Tong [29], Y.W. Wang [21], J.W. Xiang [11-13, 16-21], Z.B. Yang [14, 15, 23], X.W. Zhang [15, 23, 25], Y.H. Zhang [11], Y.T. Zhong [13].

Generally the structural analysis normally require accurate computer-intensive calculations using numerical (discrete) methods. The field of application of discrete-continual finite element method (DCFFEM), proposed by A.B. Zolotov [32] and P.A. Akimov [30-32] comprises structures with regular (in particular, constant or piecewise constant) physical and geometrical parameters in some dimension (so-called “basic” direction (dimension)). Considering problems remain continual along “basic” direction while along other directions DCFEM presupposes finite element approximation. Solution of corresponding resultant multipoint boundary problems [33] for systems of ordinary differential equations with piecewise constant coefficients and immense number of unknowns is the most time-consuming stage of the computing, especially if we take into account the limitation in performance of personal computers, contemporary software and necessity to obtain correct semianalytical solution in a reasonable time.

High-accuracy solution at all points of the model is not required normally, it is necessary to find only the most accurate solution in some pre-known domains. Generally the choice of these domains is a priori data with respect to the structure being modelled. Designers usually choose domains with the so-called edge effect (with the risk of significant stresses that could potentially lead to the destruction of structures, etc.) and regions which are subject to specific operational requirements. It is obvious that the stress-strain state in such domains is of paramount importance. Specified factors along with the obvious needs of the designer or researcher to reduce computational costs by application of DCFEM cause considerable urgency of constructing of special algorithms for obtaining local solutions (in some domains known in advance) of boundary problems. Wavelet analysis provides effective and popular tool for such researches. Solution of the considering problem within multilevel wavelet analysis is represented as a composition of local and global components. Wavelet-based DCFEM is presented in papers of P.A. Akimov [34-41], M. Aslami [37-39], T.B. Kaytukov, M.L. Mozgaleva [34-41] and O.A. Negrozov [37-39].

The distinctive paper is devoted to numerical solution of the problem of isotropic plate analysis with the use of B-spline DCFEM.

1. FORMULATIONS OF THE PROBLEM

Let the constancy of the parameters of the problem be in the direction corresponding to (main direction). The operational formulation of the problem with the use of so-called method of extended domain [42], taking into account the selection of the main direction, is determined by the equation:

$$L\,y=\widetilde{F}\,, \quad 0\le x_1\le \ell_1\,,\ 0\le x_2\le \ell_2\,, \quad (1.1)$$

where we have

$$L = -L_4\,\partial_2^4 + L_2\,\partial_2^2 + L_0\,; \qquad (1.2)$$

$$L_4 = \theta D\,; \qquad (1.3)$$

$$L_2 = -[\partial_1^2\theta D\nu + 2\partial_1\theta D(1-\nu)\partial_1 + \theta D\nu\partial_1^2]\,; \quad (1.4)$$

$$L_0 = -\partial_1^2\theta D\partial_1^2\,; \qquad (1.5)$$

$$\widetilde{F} = \theta F + \delta_\Gamma f\,; \qquad (1.6)$$

$$\theta(x_1,x_2) = \begin{cases} 1, & 0 < x_1 < \ell_1 \wedge 0 < x_2 < \ell_2 \\ 0, & \neg(0 < x_1 < \ell_1 \wedge 0 < x_2 < \ell_2); \end{cases} \quad (1.7)$$

$$\delta_\Gamma(x_1,x_2) = \partial\theta/\partial\overline{n}\,; \qquad (1.8)$$

Ω is the domain, occupied by plate; ℓ_1, ℓ_2 are corresponding dimensions of extended domain (linear dimensions of plate); $x = (x_1, x_2)$; x_1, x_2 are Cartesian coordinates; $\theta(x_1, x_2)$ is characteristic function of domain Ω; $\delta_\Gamma = \delta_\Gamma(x_1, x_2)$ is the delta function of boundary $\Gamma = \partial\Omega$; $\overline{n} = [n_1\, n_2]^T$ is boundary normal vector; y is deflection of plate; D is flexural rigidity of plate; ν is Poisson's ratio of plate; F is the load in domain Ω; $\overline{f}$ is the corresponding boundary load; $\partial_s = \partial / \partial x_s$, $s = 1, 2$. Let us introduce the following notations

$$y_1 = y\,, \quad y_2 = \partial_2 y = y_1'\,, \quad y_3 = \partial_2^2 y = y_2'\,, \quad y_4 = \partial_2^3 y = y_3'\,. \quad (1.9)$$

Thus we can rewrite (1.1):

$$-L_4 y_4' + L_2 y_3 + L_0 y_1 = \widetilde{F}\,. \qquad (1.10)$$

Finally we obtain system of differential equations with operational coefficients:

$$\begin{bmatrix} y_1' \\ y_2' \\ y_3' \\ y_4' \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ L_4^{-1}L_0 & 0 & L_4^{-1}L_2 & 0 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ -L_4^{-1}\widetilde{F} \end{bmatrix}, \qquad (1.11)$$

or

$$\overline{U}' = \widetilde{L}\overline{U} + \widetilde{\overline{F}}\,, \qquad (1.12)$$

where

$$\widetilde{L} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ L_4^{-1}L_0 & 0 & L_4^{-1}L_2 & 0 \end{bmatrix}; \qquad (1.13)$$

$$\widetilde{\overline{F}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -L_4^{-1}\widetilde{F} \end{bmatrix}; \quad \overline{U} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}. \qquad (1.14)$$

The system of equations (1.11) is supplemented by boundary conditions, which are set in sections with coordinates $x_2^1 = 0$ and $x_2^2 = \ell_2$.

2. SOME ASPECTS OF THE CONSTRUCTION OF NORMALIZED BASIS FUNCTIONS OF THE B-SPLINE

The construction of B-spline basic functions is determined by the recursive Cox-de Boer formulas [1]:

$$k = 1: \quad \varphi_{i,1}(t) = \begin{cases} 1\,, & x_i \le t < x_{i+1} \\ 0\,, & t < x_i \vee t \ge x_{i+1} \end{cases}, \qquad (2.1)$$

$$k \ge 2: \quad \varphi_{i,k}(t) = \frac{(t - x_i)\varphi_{i,k-1}(t)}{x_{i+k-1} - x_i} + \frac{(x_{i+k} - t)\varphi_{i+1,k-1}(t)}{x_{i+k} - x_{i+1}}. \qquad (2.2)$$

We will consider such a construction for the case $x_i = i$ are integers. Let us note that,

$$\varphi_{i,k}(t) = \varphi_{0,k}(t - i)$$

and therefore, recursive formulas (2.1)-(2.2) can be represented in the form

$$k = 1: \qquad \varphi_{0,1}(t) = \begin{cases} 1\,, & 0 \le t < 1 \\ 0\,, & t < 0 \vee t \ge 1; \end{cases} \qquad (2.3)$$

$$k \ge 2: \qquad \varphi_{0,k}(t) = \frac{1}{k-1}[t \cdot \varphi_{0,k-1}(t) + (k-t)\varphi_{0,k-1}(t-1)]. \qquad (2.4)$$

The function $\varphi_{0,1}(t)$ can be represented by formula

$$\varphi_{0,1}(t) = \frac{1}{2}[\mathrm{sign}(t) - \mathrm{sign}(t-1)]\,. \qquad (2.5)$$

Let us denote by the operator of the first difference. Then we have

$$\varphi_{0,1}(t) = -\frac{1}{2}\Delta_1 \operatorname{sign}(t). \qquad (2.6)$$

We can substitute formula (2.5) into (2.4) in order to determine $\varphi_{0,2}(t)$:

$$\begin{aligned}\varphi_{0,2}(t) &= 1\cdot[t\cdot\varphi_{0,1}(t) + (2-t)\varphi_{0,1}(t-1)] = \\ &= \frac{1}{2}\{t\cdot[\operatorname{sign}(t) - \operatorname{sign}(t-1)] + \\ &(2-t)[\operatorname{sign}(t-1) - \operatorname{sign}(t-2)]\} = \\ &= \frac{1}{2}[t\operatorname{sign}(t) - 2(t-1)\operatorname{sign}(t-1) + \\ &(t-2)\operatorname{sign}(t-2)] = \frac{1}{2}[|t| - 2|t-1| + |t-2|.\end{aligned}$$

Let us denote by Δ_2 the operator of the second difference. Then we have

$$\varphi_{0,2}(t) = \frac{1}{2}[|t| - 2|t-1| + |t-2| = \frac{1}{2}\Delta_2 |t-1|. \qquad (2.7)$$

We can define function $\varphi_{0,3}(t)$:

$$\varphi_{0,3}(t) = \frac{1}{2}[t\cdot\varphi_{0,2}(t) + (3-t)\varphi_{0,2}(t-1)].$$

Omitting intermediate calculations, we get

$$\begin{aligned}\varphi_{0,3}(t) &= \frac{1}{4}[t\cdot|t| - 3(t-1)|t-1| + \\ &+ 3(t-2)|t-2| - (t-3)|t-3|] = \\ &= -\frac{1}{2!}\frac{1}{2}\Delta_1\Delta_2((t-1)|t-1|). \qquad (2.8)\end{aligned}$$

Based on formulas (2.8) and (2.4), we can define the function

$$\varphi_{0,4}(t) = \frac{1}{3}[t\cdot\varphi_{0,3}(t) + (4-t)\varphi_{0,3}(t-1)].$$

Omitting intermediate calculations, as a result we get

$$\begin{aligned}\varphi_{0,4}(t) &= \\ &= \frac{1}{2\cdot 3}\cdot\frac{1}{2}[t^2\cdot|t| - 4(t-1)^2|t-1| + \\ &+ 6(t-2)^2|t-2| - 4(t-3)^2|t-3| + \\ &+ (t-4)^2|t-4|] = \\ &= \frac{1}{3!}\frac{1}{2}(\Delta_2)^2((t-2)^2|t-2|). \qquad (2.9)\end{aligned}$$

It can be proved that for even $k = 2m$ we have

$$\varphi_{0,k}(t) = \frac{1}{(2m-1)!}\frac{1}{2}(\Delta_2)^m((t-m)^{2m-2}|t-m|) \qquad (2.10)$$

and for odd (uneven) $k = 2m + 1$ we have

$$\varphi_{0,k}(t) = -\frac{1}{(2m)!}\frac{1}{2}\Delta_1(\Delta_2)^m((t-m)^{2m-1}|t-1|). \qquad (2.11)$$

Note that $\varphi_{0,k}(t)$ is a polynomial of degree $k-1$ with bounded support and, as follows from the difference operator, this support is equal to the interval $[0, k]$. In addition, we should note the following property of B-spline basis functions:

$$\sum_i \varphi_{0,k}(t-i) \equiv 1 \text{ for arbitrary } t. \qquad (2.12)$$

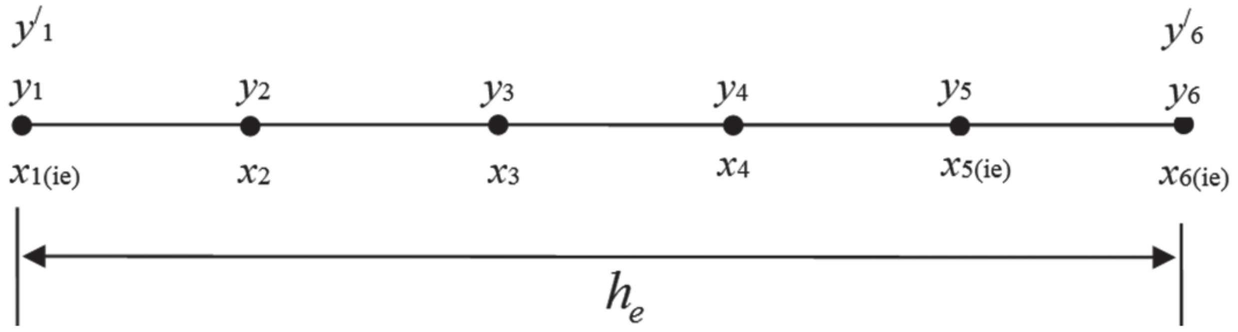


Figure 3.1. Finite element discretication (sample)

3. SOME GENERAL ASPECTS OF FINITE ELEMENT APPROXIMATION

The discrete component of the numerical solution is represented by the direction along the axis corresponding to x_1. The fulfillment within an element (interval) for all components of a vector function $\overline{U}$ (see (1.14)) is the same. Therefore, let us use the following notation for simplicity:

$$x = x_1,\ \ell = \ell_1,\ y = y_1,\ j = 1, 2, 3, 4. \qquad (3.1)$$

Let us divide the interval $(0,\ \ell)$ segment into N_e parts (elements). Therefore $h_e = \ell/N_e$ is the length of the element. Besides, let us also divide each element into N_k parts, for example, $N_k = 5$ (see Figure 3.1).

Let us use the following notation system: i_e is the element number; $x_1(i_e)$ is the coordinate of the starting point of the i_e-th element; $x_6(i_e)$ is the coordinate of the end point of the i_e-th element. We y_i and $y'_i = \partial_1 y(x_i)$, $i = 1{,}6$ take as unknowns at the boundary points. Besides, we take y_i, $i = 2, 3, 4, 5$ as unknowns and at the inner points. Thus, the number of unknowns per element with such a approximation is equal to

$$N = N_k - 1 + 2 \cdot 2 = N_k + 3 = 8.$$

4. LOCAL CONSTRUCTIONS FOR ARBITRARY FINITE ELEMENT

Let us introduce local coordinates:

$$t = \frac{x - x_{1(i_e)}}{h_e},\ \ x_{1(i_e)} \le x \le x_{6(i_e)},\ \ 0 \le t \le 1. \qquad (4.1)$$

In this case, we have the following relations:

$$\begin{cases} x = x_{1(i_e)} & \Rightarrow t = 0 \\ x = x_2 & \Rightarrow t = 0.2 \\ x = x_3 & \Rightarrow t = 0.4 \\ x = x_4 & \Rightarrow t = 0.6 \\ x = x_5 & \Rightarrow t = 0.8 \\ x = x_{6(i_e)} & \Rightarrow t = 1 \end{cases}, \qquad \begin{array}{c} \dfrac{d}{dx} = \dfrac{d}{dt} \cdot \dfrac{dt}{dx} = \dfrac{1}{h_e}\dfrac{d}{dt} \\ \dfrac{d^p}{dx^p} = \dfrac{1}{h_e^p}\dfrac{d^p}{dt^p} \end{array},$$

$$dx = h_e \cdot dt. \qquad (4.2)$$

Since the number of unknowns on the element is equal to $N = 8$, we use a B-spline of the seventh degree in order to represent the unknown deflection function.

Let us use the following notation:

$$\varphi(t) = \varphi_{0,8}(t+4);$$

$$\begin{aligned} \varphi(t) = \frac{1}{7!}\frac{1}{2}(\Delta_2)^4(t^6\,|\,t\,|) = \\ = \frac{1}{2\cdot 7!}[(t+4)^6\,|\,t+4\,| - \\ - 8(t+3)^6\,|\,t+3\,| + \\ + 28(t+2)^6\,|\,t+2\,| - \\ - 56(t+1)^6\,|\,t+1\,| + 70t^6\,|\,t\,| - \\ - 56(t-1)^6\,|\,t-1\,| + 28(t-2)^6\,|\,t-2\,| - \\ - 8(t-3)^6\,|\,t-3\,| + (t-4)^6\,|\,t-4\,|]. \end{aligned} \qquad (4.3)$$

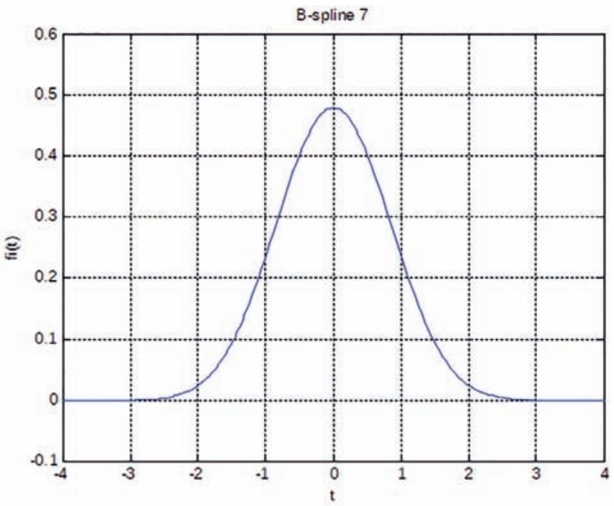


Figure 4.1. B-spline of the seventh order $\varphi(t) = \varphi_{0,8}(t + 4)$

Let us use the following notation system:

$$\begin{gathered} \varphi_1(t) = \varphi(t+3),\ \varphi_2(t) = \varphi(t+2), \\ \varphi_3(t) = \varphi(t+1),\ \varphi_4(t) = \varphi(t), \\ \varphi_5(t) = \varphi(t-1), \\ \varphi_6(t) = \varphi(t-2),\ \varphi_7(t) = \varphi(t-3), \\ \varphi_8(t) = \varphi(t-4),\ \ 0 \le t \le 1. \end{gathered} \qquad (4.4)$$

We represent the unknown deflection function in the form

$$y(x) = w(t) = \sum_{k=1}^{N} \alpha_k \varphi_k(t), \quad x_{1(i_e)} \le x \le x_{6(i_e)},$$
$$0 \le t \le 1. \quad (4.5)$$

We have to consider bilinear forms with allowance for relations (4.2) in order to construct local stiffness matrices corresponding to the operators L_0, L_2 and L_4 (see (1.3)-(1.5)):

$$B_0(y,z) = < L_0 y, z > = -\int_{x_{1(i_e)}}^{x_{5(i_e)}} \frac{d^2}{dx^2}\theta D \frac{d^2 y}{dx^2}\cdot z\,dx =$$
$$= -\theta_{i_e} D_{i_e}\int_{x_{1(i_e)}}^{x_{5(i_e)}} \frac{d^2 y}{dx^2}\cdot\frac{d^2 z}{dx^2}\,dx =$$
$$= -\frac{1}{h_e^3}\theta_{i_e} D_{i_e}\int_0^1 \frac{d^2 w}{dt^2}\cdot\frac{d^2 v}{dt^2}\,dt = B_0(w,v); \ (4.6)$$

$$B_4(y,z) = < L_4 y, z > = \theta_{i_e} D_{i_e}\int_{x_{1(i_e)}}^{x_{5(i_e)}} y\cdot z\,dx =$$
$$= h_e\theta_{i_e} D_{i_e}\int_0^1 w\cdot v\,dt = B_4(w,v); \quad (4.7)$$

$$B_2(y,z) = < L_2 y, z > = < L_{21} y, z > +$$
$$+ < L_{22} y, z > + < L_{23} y, z >, \quad (4.8)$$

where

$$< L_{21} y, z > = -\theta_{i_e} D_{i_e}\nu_{i_e}\int_{x_{1(i_e)}}^{x_{5(i_e)}} \frac{d^2 y}{dx^2} z\,dx =$$
$$= -\frac{1}{h_e}\theta_{i_e} D_{i_e}\nu_{i_e}\int_0^1 \frac{d^2 w}{dt^2} v\,dt = B_{21}(w,v); \quad (4.9)$$

$$< L_{23} y, z > = -\theta_{i_e} D_{i_e}\nu_{i_e}\int_{x_{1(i_e)}}^{x_{5(i_e)}} y\cdot\frac{d^2 z}{dx^2}\,dx =$$
$$= -\frac{1}{h_e}\theta_{i_e} D_{i_e}\nu_{i_e}\int_0^1 w\cdot\frac{d^2 v}{dt^2}\,dt = B_{23}(w,v); \quad (4.10)$$

$$< L_{22} y, z > = -2\int_{x_{1(i_e)}}^{x_{5(i_e)}} \frac{d}{dx}\theta D(1-\nu)\frac{dy}{dx}\cdot z\,dx =$$
$$= 2\theta_{i_e} D_{i_e}(1-\nu_{i_e})\int_{x_{1(i_e)}}^{x_{5(i_e)}} \frac{dy}{dx}\cdot\frac{dz}{dx}\,dx =$$
$$= \frac{1}{h_e} 2\theta_{i_e} D_{i_e}(1-\nu_{i_e})\int_0^1 \frac{dw}{dt}\cdot\frac{dv}{dt}\,dt = B_{22}(w,v).$$
$$(4.11)$$

for the following type of functions

$$y(x) = w(t) = \sum_{k=1}^{N} \alpha_k \varphi_k(t),$$
$$z(x) = v(t) = \sum_{k=1}^{N} \beta_k \varphi_k(t),$$
$$x_{1(i_e)} \le x \le x_{6(i_e)}, \ 0 \le t \le 1 \ (4.12)$$

Let us substitute (4.12) into (4.6)-(4.11):

$$B_0(w,v) = -\frac{1}{h_e^3}\theta_{i_e} D_{i_e}\int_0^1 \frac{d^2 w}{dt^2}\cdot\frac{d^2 v}{dt^2}\,dt =$$
$$= -\frac{\theta_{i_e} D_{i_e}}{h_e^3}\sum_{i=1}^{N}\sum_{j=1}^{N}\alpha_i\beta_j\int_0^1 \varphi_i''(t)\varphi_j''(t)\,dt =$$
$$= -\frac{\theta_{i_e} D_{i_e}}{h_e^3}(K^0_{\alpha\beta}\overline{\alpha},\overline{\beta}), \quad (4.13)$$

where

$$K^0_{\alpha\beta}(i,j) = \int_0^1 \varphi_i''(t)\varphi_j''(t)\,dt; \quad \varphi'' = \frac{d^2\varphi}{dt^2}; \quad (4.14)$$

$$B_4(w,v) = h_e\theta_{i_e} D_{i_e}\int_0^1 w\cdot v\,dt =$$
$$= \theta_{i_e} D_{i_e} h_e\sum_{i=1}^{N}\sum_{j=1}^{N}\alpha_i\beta_j\int_0^1 \varphi_i(t)\varphi_j(t)\,dt =$$
$$= h_e\theta_{i_e} D_{i_e}(K^4_{\alpha\beta}\overline{\alpha},\overline{\beta}), \quad (4.15)$$

where

$$K^4_{\alpha\beta}(i,j) = \int_0^1 \varphi_i(t)\varphi_j(t)\,dt; \quad (4.16)$$

$$B_{21}(w,v) = -\frac{1}{h_e}\theta_{i_e} D_{i_e}\nu_{i_e}\int_0^1 \frac{d^2 w}{dt^2} v\,dt =$$
$$= -\frac{\theta_{i_e} D_{i_e}\nu_{i_e}}{h_e}\sum_{i=1}^{N}\sum_{j=1}^{N}\alpha_i\beta_j\int_0^1 \varphi_i''(t)\varphi_j(t)\,dt =$$
$$= -\frac{\theta_{i_e} D_{i_e}\nu_{i_e}}{h_e}(K^{21}_{\alpha\beta}\overline{\alpha},\overline{\beta}), \quad (4.17)$$

where

$$K^{21}_{\alpha\beta}(i,j)=\int_0^1 \varphi''_i(t)\varphi_j(t)\,dt\,; \qquad (4.18)$$

$$B_{23}(w,v)=-\frac{1}{h_e}\theta_{i_e}D_{i_e}\nu_{i_e}\int_0^1 w\cdot\frac{d^2v}{dt^2}dt=$$
$$=-\frac{\theta_{i_e}D_{i_e}\nu_{i_e}}{h_e}\sum_{i=1}^{N}\sum_{j=1}^{N}\alpha_i\beta_j\int_0^1\varphi_i(t)\varphi''_j(t)\,dt=$$
$$=-\frac{\theta_{i_e}D_{i_e}\nu_{i_e}}{h_e}(K^{23}_{\alpha\beta}\overline{\alpha},\overline{\beta}), \quad (4.19)$$

where

$$K^{23}_{\alpha\beta}(i,j)=\int_0^1\varphi_i(t)\varphi''_j(t)\,dt=K^{21}_{\alpha\beta}(j,i)\,; \quad (4.20)$$

$$B_{22}(w,v)=\frac{1}{h_e}2\theta_{i_e}D_{i_e}(1-\nu_{i_e})\int_0^1\frac{dw}{dt}\cdot\frac{dv}{dt}dt=$$
$$=2\frac{\theta_{i_e}D_{i_e}(1-\nu_{i_e})}{h_e}\sum_{i=1}^{N}\sum_{j=1}^{N}\alpha_i\beta_j\int_0^1\varphi'_i(t)\varphi'_j(t)\,dt=$$
$$=2\frac{\theta_{i_e}D_{i_e}(1-\nu_{i_e})}{h_e}(K^{22}_{\alpha\beta}\overline{\alpha},\overline{\beta}), \quad (4.21)$$

where

$$K^{22}_{\alpha\beta}(i,j)=\int_0^1\varphi'_i(t)\varphi'_j(t)\,dt\,, \quad \varphi'=\frac{d\varphi}{dt}. \quad (4.22)$$

Let us define the parameters α_k and β_k through the nodal unknowns on the element:

$$\begin{cases} y_1=w(0)=\sum_{k=1}^{N}\alpha_k\varphi_k(0)\\ \dfrac{dy_1}{dx}=\dfrac{1}{h_e}w'(0)=\dfrac{1}{h_e}\sum_{k=1}^{N}\alpha_k\varphi'_k(0)\\ y_2=w(0.2)=\sum_{k=1}^{N}\alpha_k\varphi_k(0.2)\\ y_3=w(0.4)=\sum_{k=1}^{N}\alpha_k\varphi_k(0.4)\\ y_4=w(0.6)=\sum_{k=1}^{N}\alpha_k\varphi_k(0.6)\\ y_5=w(0.8)=\sum_{k=1}^{N}\alpha_k\varphi_k(0.8)\\ y_6=w(1)=\sum_{k=1}^{N}\alpha_k\varphi_k(1)\\ \dfrac{dy_6}{dx}=\dfrac{1}{h_e}w'(1)=\dfrac{1}{h_e}\sum_{k=1}^{N}\alpha_k\varphi'_k(1)\end{cases} \qquad (4.23)$$

Therefor we have

$$\overline{y}^{i_e}=T\overline{\alpha}\,, \qquad (4.24)$$

where (see also (4.27))

$$\overline{y}^{i_e}=[y_1\ \ \frac{dy_1}{dx}\ \ y_2\ \ y_3\ \ y_4\ \ y_5\ \ y_6\ \ \frac{dy_6}{dx}]^{\mathrm{T}}\ ; \quad (4.25)$$
$$\overline{\alpha}=[\alpha_1\ \ \alpha_2\ \ \alpha_3\ \ \alpha_4\ \ \alpha_5\ \ \alpha_6\ \ \alpha_7\ \ \alpha_8]^{\mathrm{T}}\ ; \quad (4.26)$$
$$D=diag(1\ \ 1/h_e\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1/h_e)\,. \quad (4.27)$$

$$T=D\begin{bmatrix} \varphi_1(0) & \varphi_2(0) & \varphi_3(0) & \varphi_4(0) & \varphi_5(0) & \varphi_6(0) & \varphi_7(0) & \varphi_8(0)\\ \varphi'_1(0) & \varphi'_2(0) & \varphi'_3(0) & \varphi'_4(0) & \varphi'_5(0) & \varphi'_6(0) & \varphi'_7(0) & \varphi'_8(0)\\ \varphi_1(0.2) & \varphi_2(0.2) & \varphi_3(0.2) & \varphi_4(0.2) & \varphi_5(0.2) & \varphi_6(0.2) & \varphi_7(0.2) & \varphi_8(0.2)\\ \varphi_1(0.4) & \varphi_2(0.4) & \varphi_3(0.4) & \varphi_4(0.4) & \varphi_5(0.4) & \varphi_6(0.4) & \varphi_7(0.4) & \varphi_8(0.4)\\ \varphi_1(0.6) & \varphi_2(0.6) & \varphi_3(0.6) & \varphi_4(0.6) & \varphi_5(0.6) & \varphi_6(0.6) & \varphi_7(0.6) & \varphi_8(0.6)\\ \varphi_1(0.8) & \varphi_2(0.8) & \varphi_3(0.8) & \varphi_4(0.8) & \varphi_5(0.8) & \varphi_6(0.8) & \varphi_7(0.8) & \varphi_8(0.8)\\ \varphi_1(1) & \varphi_2(1) & \varphi_3(1) & \varphi_4(1) & \varphi_5(1) & \varphi_6(1) & \varphi_7(1) & \varphi_8(1)\\ \varphi'_1(1) & \varphi'_2(1) & \varphi'_3(1) & \varphi'_4(1) & \varphi'_5(1) & \varphi'_6(1) & \varphi'_7(1) & \varphi'_8(1) \end{bmatrix}, \quad (4.28)$$

Similarly, we get

$$\overline{z}^{i_e}=T\overline{\beta}\,. \qquad (4.29)$$

From (4.23) and (4.28) it follows

$$\overline{\alpha}=T^{-1}\overline{y}^{i_e}\,; \quad \overline{\beta}=T^{-1}\overline{z}^{i_e}\,. \qquad (4.30)$$

We have the following chain of equalities

$$(K_{\alpha\beta}\overline{\alpha},\overline{\beta}) = (K_{\alpha\beta}T^{-1}\overline{y}^{i_e}, T^{-1}\overline{z}^{i_e}) = \\ = ((T^{-1})^{\mathrm{T}} K_{\alpha\beta}T^{-1}\overline{y}^{i_e}, \overline{z}^{i_e}). \quad (4.31)$$

Therefore, substituting (4.30) sequentially in (4.13), (4.15), (4.17), (4.19), (4.21), we obtain local stiffness matrices $K_0^{i_e}$, $K_4^{i_e}$, $K_{21}^{i_e}$, $K_{23}^{i_e}$, $K_{22}^{i_e}$, $K_2^{i_e}$, corresponding to the operators L_0, L_4, L_{21}, L_{23}, L_{22}, L_2.

$$K_0^{i_e} = -\frac{\theta_{i_e} D_{i_e}}{h_e^3}(T^{-1})^{\mathrm{T}} K_{\alpha\beta}^0 T^{-1}; \quad (4.32)$$

$$K_4^{i_e} = h_e \theta_{i_e} D_{i_e} (T^{-1})^{\mathrm{T}} K_{\alpha\beta}^4 T^{-1}; \quad (4.33)$$

$$K_{21}^{i_e} = -\frac{\theta_{i_e} D_{i_e} \nu_{i_e}}{h_e}(T^{-1})^{\mathrm{T}} K_{\alpha\beta}^{21} T^{-1}; \quad (4.34)$$

$$K_{23}^{i_e} = -\frac{\theta_{i_e} D_{i_e} \nu_{i_e}}{h_e}(T^{-1})^{\mathrm{T}} K_{\alpha\beta}^{23} T^{-1} = (K_{21}^{i_e})^{\mathrm{T}}; \quad (4.35)$$

$$K_{22}^{i_e} = 2\frac{\theta_{i_e} D_{i_e}(1-\nu_{i_e})}{h_e}(T^{-1})^{\mathrm{T}} K_{\alpha\beta}^{22} T^{-1}. \quad (4.36)$$

Since $L_2 = L_{21} + L_{22} + L_{23}$ the corresponding local stiffness matrix has the form:

$$K_2^{i_e} = K_{21}^{i_e} + K_{22}^{i_e} + K_{23}^{i_e}. \quad (4.37)$$

5. INFORMATION ABOUT NUMERICAL IMPLEMENTATION

The presented algorithm can be implemented using MATLAB tools. The MATLAB system has convenient functions for working with polynomials. Moreover, the main parameter of these functions is the vector of coefficients of the polynomial. To determine the coefficients of basic polynomials φ_k on an interval [0 1], we can firstly determine their values at eight points of the interval $t = [t_1, t_2, ..., t_8]$, $t_i \in [0\ \ 1]$, $i = 1, 2, ..., 8$:

$$F_k(i) = \varphi_k(t_i),\ i = 1, 2, ..., 8,\ k = 1, 2, ..., 8.$$

Then, using the `polyfit` function, we define their coefficient vector:

```
pk=polyfit(t,Fk,7)
```

This function is used to determine the coefficients of the optimal polynomial using the least squares method. In the considering case, we are looking for a polynomial of the 7th degree (i.e. we have to define 8 coefficients of polynomial, according to its 8 values), therefore, we get a polynomial passing through the given values.

In order to calculate the derivatives we can sequentially use the `polyder` function:

```
dpk=polyder(pk)
```
is the vector of coefficients φ'_k;
```
d2pk=polyder(dpk)
```
is the vector of coefficients φ''_k.

In order to calculate the product of polynomials we can use the conv function:

```
pij=conv(pi, pj)
```
is the vector of coefficients $\varphi_i\varphi_j$;
```
d20pij=conv(d2pi, pj)
```
is the vector of coefficients $\varphi''_i\varphi_j$;
```
d02pij=conv(pi, d2pj)
```
is the vector of coefficients $\varphi_i\varphi''_j$;
```
dpij=conv(dpi, dpj)
```
is the vector of coefficients $\varphi'_i\varphi'_j$;
```
d2pij=conv(d2pi, d2pj)
```
is the vector of coefficients $\varphi''_i\varphi''_j$.

In order to calculate the antiderivative of a polynomial we can use the `polyint` function:

```
Pi=polyint(pi)
```
is the vector of coefficients $\int\varphi_i dt$;
```
Pij=polyint(pij)
```
is the vector of coefficients $\int\varphi_i\varphi_j dt$;
```
d20Pij=polyint(d20pij)
```
is the vector of coefficients $\int\varphi''_i\varphi_j dt$;
```
d02Pij=polyint(d02pij)
```
is the vector of coefficients $\int\varphi_i\varphi''_j dt$;
```
dPij=polyint(dpij)
```
is the vector of coefficients $\int\varphi'_i\varphi'_j dt$;
```
d2Pij=polyint(d2pij)
```
is the vector of coefficients $\int\varphi''_i\varphi''_j dt$.

Then the calculation of matrices $K^0_{\alpha\beta}(i,j)$, $K^4_{\alpha\beta}(i,j)$, $K^{21}_{\alpha\beta}(i,j)$, $K^{23}_{\alpha\beta}(i,j)$, $K^{22}_{\alpha\beta}(i,j)$ can be done in the following algorithm:

$K^0_{\alpha\beta}(i,j)=$ `polyval(d2Pij,1)-polyval(d2Pij,0);`

$K^4_{\alpha\beta}(i,j)=$ `polyval(Pij,1)-polyval(Pij,0),`

$K^{21}_{\alpha\beta}(i,j)=$ `polyval(d20Pij,1)-polyval(d20Pij,0),`

$K^{23}_{\alpha\beta}(i,j)=$ `polyval(d02Pij,1)-polyval(d02Pij,0),`

$K^{22}_{\alpha\beta}(i,j)=$ `polyval(dPij,1)-polyval(dPij,0),`

where the function `polyval (p, t)` allows researcher to calculate the values of a polynomial with a vector of coefficients *p* at a given point *t*.

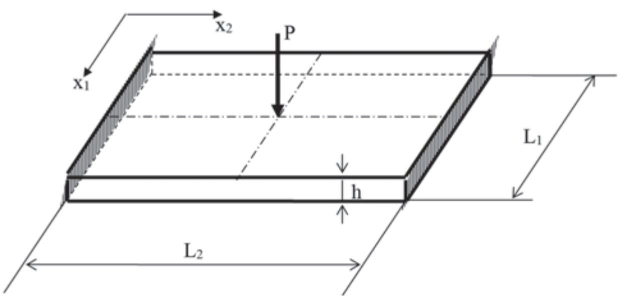


Figure 6.1. Example of analysis

6. EXAMPLE OF ANALYSIS

Let us consider the problem of the bending of a thin plate rigidly fixed along the side faces under the influence of a load concentrated in the center as an example (Figure 6.1).
Let us consider the following geometric parameters: $L_1 = 0.9$ m, $L_2 = 1.0$ m, $h = 0.05$ m is the thickness.
Let us consider the following design parameters of material of plate: coefficient of elasticity $E = 3000 \cdot 10^4$ kN/m², Poisson's ratio $\nu = 0.16$.
Let external load parameter be equal to $P = 1$ kN.
Let the number of elements be equal to $N_e = 4$.

Then we have the following element length:

$$h_e = L_1 / N_e = 0{,}9/4 = 0{,}225.$$

Distance between the coordinates of the nodes is equal to

$$h_p = h_e / 5 = 0{,}225/5 = 0{,}045.$$

The number of nodal unknowns for each component of the vector function y_j, $j = 1, 2, 3, 4$ is equal to

$$N_g = N_p + 2N_b = 4 \cdot (5-1) + 2 \cdot (4+1) = 26,$$

where $N_p = N_e(N_k - 1)$ is the total number of internal nodes for all elements; $N_b = N_e + 1$ is the total number of border nodes for all elements.
The total number of unknowns is equal to

$$N_U = 4N_g = 4 \cdot 26 = 104.$$

Let us conventional finite element method (FEM) for comparison. Unknown functions on an element within FEM are represented as a cubic parabola and at a node each unknown function is represented by two unknown nodal quantities: the nodal value of the unknown function itself and its first derivative in the discrete direction. In this case the total number of nodal points in the discrete direction corresponding to x_1 is equal to

$$N_1 = L_1 / N_p + 1 = 0{,}9 / 0{,}045 + 1 = 21.$$

The number of nodal unknowns for each component of the vector function y_j, $j = 1, 2, 3, 4$ is equal to

$$N_g = 2N_1 = 42.$$

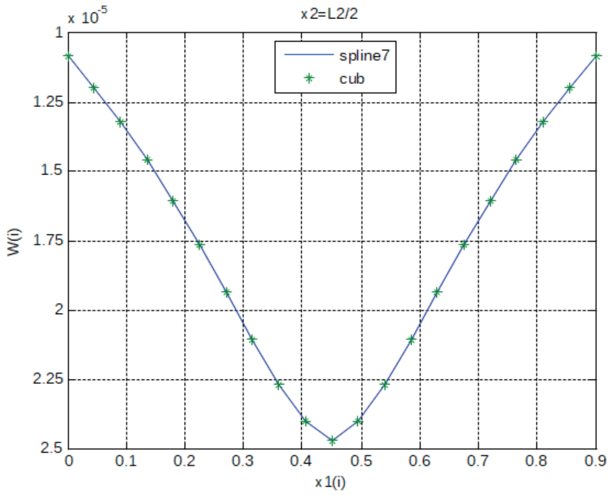
The total number of unknowns is equal to

$$N_U = 4N_g = 4 \cdot 42 = 168.$$

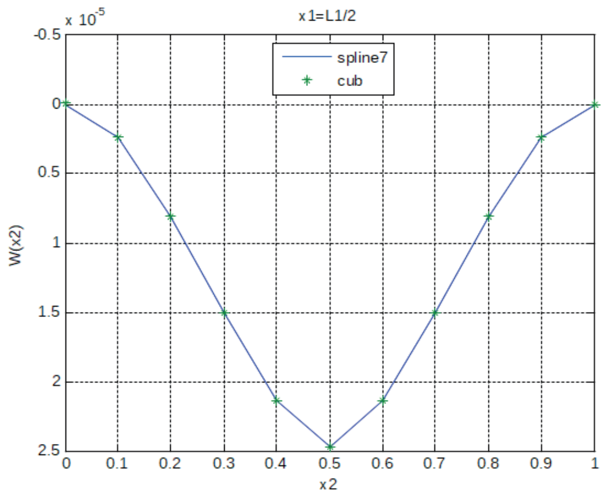
The graphical comparison of results of analysis is presented at Figures 6.2, 6.3, where `spline7` corresponds to deflection values, obtained using 7th order B-splines; `cub` corresponds to deflection values obtained using the traditional finite element method; $h_1 = h_p = 0{,}045$ and $h_2 = 0{,}1$ are steps for printing results along directions corresponding to x_1 and x_2.

As researcher can see, the results obtained are almost completely identical. And at the same time, the algorithm of the discrete-continual finite element method based on the use of B-splines leads to a significant reduction in the number of unknowns. The difference is equal to

$$4N_p = 4N_e(N_k - 1) = 4 \cdot 4 \cdot (5 - 1) = 64.$$



Figures 6.2. Comparison of the results of analysis in the middle sections along direction



Figures 6.3. Comparison of the results of analysis in the middle sections along direction

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REFERENCES

1. **Akimov P.A., Mozgaleva M.L., Kaytukov T.B.** Numerical solution of the problem of beam analysis with the use of B-spline finite element method. // International Journal for Computational Civil and Structural Engineering, 2020, Vol. 16, Issue 3, pp. 12–22.
2. **Li B., Chen X.** Wavelet-based numerical analysis: A review and classification. // Finite Elements in Analysis and Design, 2014, Vol. 81, pp. 14–31.
3. **Daubechies I.** Orthonormal bases of compactly supported wavelets. // Commun. Pure Appl. Math., 1988, Vol. 41, pp. 909–996.
4. **Li B., Cao H.R., He Z.J.** The construction of one-dimensional Daubechies wavelet-based finite elements for structural response analysis. // J. Vibroeng, 2011, vol. 13, pp. 729–738.
5. **Ma J.R., Xue J.J.** A study of the construction and application of a Daubechies wave-let-based beam element. // Finite Elements in Analysis and Design, 2003, Vol. 39, pp. 965–975.
6. **Mozgaleva M.L., Akimov P.A., Kaytukov T.B.** About wavelet-based computational

beam analysis with the use of Daubechies scaling functions. // International Journal for Computational Civil and Structural Engineering, 2019, Vol. 15, Issue 2, pp. 95–110.
7. **Mozgaleva M.L., Akimov P.A., Kaytukov T.B.** Wavelet-based discrete-continual finite element plate analysis with the use of Daubechies scaling functions. // International Journal for Computational Civil and Structural Engineering, 2019, Vol. 15, Issue 3, pp. 96–108.
8. **Antes H.** Bicubic fundamental splines in plate bending. // Int. J. Numer. Methods Eng., 1974, Vol. 8, pp. 503–511.
9. **Han J.G., Ren W.X., Huang Y.** A spline wavelet finite-element method in structural mechanics. // Int. J. Numer. Methods Eng., 2006, Vol. 66, pp. 166–190.
10. **Han J.G., Ren W.X., Huang Y.** A spline wavelet finite element formulation of thin plate bending. // Eng. Comput., 2009, Vol. 25, pp. 319–326.
11. **Xiang J.W., Chen X.F., He Z.J., Zhang Y.H.** A new wavelet-based thin plate element using B-spline wavelet on the interval. // Comput. Math., 2008, Vol. 41, pp. 243–255.
12. **Chen X.F., Xiang J.W., Li B., He Z.J.** A study of multiscale wavelet-based elements for adaptive finite element analysis. // Adv. Eng. Softw., 2010, Vol. 41, pp. 196–205.
13. **Zhong Y.T., Xiang J.W.** Construction of wavelet-based elements for static and stability analysis of elastic problems. // Acta Mech. Solida Sin., 2011, Vol. 24, pp. 355–364.
14. **Yang Z.B., Chen X.F., Li B., He Z.J., Miao H.H.** Vibration analysis of curved shell using b-spline wavelet on the interval (BSWI). // Finite Elements Method and General Shell Theory, CMES85, 2012, pp. 129–155.
15. **Yang Z.B., Chen X.F., Zhang X.W., He Z.J**. Free vibration and buckling analysis of plates using B-spline wavelet on the interval Mindlin element. // Appl. Math. Model., 2013, Vol. 37, pp. 3449-3466.
16. **Xiang J.W., Chen X.F., Li B., He Y.M., He Z.J.** Identification of a crack in a beam based on the finite element method of a B-spline wavelet on the interval. // J. Sound Vibr., 2006, Vol. 296, pp. 1046–1052.
17. **Xiang J.W., Chen X.F., Mo Q.M., He Z.H.** Identification of crack in a rotor system based on wavelet finite element method. // Finite Elem. Anal. Des., 2007, Vol. 43, pp. 1068–1081.
18. **Xiang J.W., Liang M.** A two-step approach to multi-damage detection for plate structures. // Eng. Fract. Mech., 2012, Vol. 91, pp. 73–86.
19. **Xiang J.W., Matsumoto T., Long J.Q., Ma G**. Identification of damage locations based on operating deflection shape. // Nondestruct. Test. Eval., 2012, Vol. 1, pp. 1–15.
20. **Xiang J.W., Liang M.** Wavelet-based detection of beam cracks using modal shape and frequency measurements. // Comput.-Aided Civil Infrastruct. Eng., 2012, Vol. 27, pp. 439–454.
21. **Xiang J.W., Matsumoto T., Wang Y.W., Jiang Z.S.** Detect damages in conical shells using curvature mode shape and wavelet finite element method. // Int. J. Mech. Sci., 2013, Vol. 66, pp. 83–93.
22. **Dong H.B., Chen X.F., Li B., Qi K.Y., He Z.J.** Rotor crack detection based on high-precision modal parameter identification method and wavelet finite element model. // Mech. Syst. Signal Process., 2009, Vol. 23, pp. 869–883.
23. **Chen X.F., Yang Z.B., Zhang X.W., He Z.J.** Modeling of wave propagation in one-dimension structures using B-spline wavelet on interval finite element. // Finite Elem. Anal. Des., 2012, Vol. 51, pp. 1–9.
24. **Han J.G., Ren W.X., Huang Y.** A multivariable wavelet-based finite element method and its application to thick plates. // Finite Elem. Anal. Des., 2005, Vol. 41, pp. 821–833.
25. **Zhang X.W., Chen X.F., He Z.J.** The analysis of shallow shells based on multivariable wavelet finite element method. // Acta Mech. Solida Sin., 2011, Vol. 24, pp. 450–460.
26. **Han J.G., Ren W.X., Huang Y.** A wavelet-based stochastic finite element method of thin plate bending. // Appl. Math. Model., 2007, Vol. 31, pp. 181–193.

27. **Pian T.H.H., Chen D.P.** Alternative ways for formulation of hybrid stress elements. // Int. J. Numer. Methods Eng., 1982, Vol. 18, pp. 1679–1684.
28. **Pian T.H.H., Sumihara K.** Rational approach for assumed stress finite elements. // Int. J. Numer. Methods Eng., 1984, Vol. 20, pp. 1685–1695.
29. **Mau S.T., Tong P., Pian T.H.H.** Finite element solutions for laminated thick plates. // J. Compos. Mater., 1972, Vol. 6, pp. 304–311.
30. **Akimov P.A.** Correct Discrete-Continual Finite Element Method of Structural Analysis Based on Precise Analytical Solutions of Resulting Multipoint Boundary Problems for Systems of Ordinary Differential Equations. // Applied Mechanics and Materials, 2012, Vols. 204–208, pp. 4502–4505.
31. **Akimov P.A., Belostotskiy A.M., Mozgaleva M.L., Mojtaba Aslami, Negrozov O.A.** Correct Multilevel Discrete-Continual Finite Element Method of Structural Analysis. // Advanced Materials Research, 2014, Vol. 1040, pp. 664–669.
32. **Zolotov A.B., Akimov P.A.** Semianalytical Finite Element Method for Two-dimensional and Three-dimensional Problems of Structural Analysis. // Proceedings of the International Symposium LSCE 2002 organized by Polish Chapter of IASS, Warsaw, Poland, 2002, pp. 431–440.
33. **Akimov P.A., Sidorov V.N.** Correct Method of Analytical Solution of Multipoint Boundary Problems of Structural Analysis for Systems of Ordinary Differential Equations with Piecewise Constant Coefficients. // Advanced Materials Research, 2011, Vols. 250–253, pp. 3652–3655.
34. **Akimov P.A., Mozgaleva M.L.** Correct Wavelet-based Multilevel Discrete-Continual Methods for Local Solution of Boundary Problems of Structural Analysis. // Applied Mechanics and Materials, 2013, Vols. 353–356, pp. 3224–3227.
35. **Akimov P.A., Mozgaleva M.L.** Wavelet-based Multilevel Discrete-Continual Finite Element Method for Local Deep Beam Analysis. // Applied Mechanics and Materials, 2013, Vols. 405–408, pp. 3165–3168.
36. **Akimov P.A., Mozgaleva M.L.** Wavelet-based Multilevel Discrete-Continual Finite Element Method for Local Plate Analysis. // Applied Mechanics and Materials, 2013, Vols. 351–352, pp. 13–16.
37. **Akimov P.A., Mozgaleva M.L., Mojtaba Aslami, Negrozov O.A.** Modified Wavelet-based Multilevel Discrete-Continual Finite Element Method for Local Structural Analysis. Part 1: Continual and Discrete-Continual Formulations of the Problems. // Applied Mechanics and Materials, 2014, Vols. 670–671, pp.720–723.
38. **Akimov P.A., Mozgaleva M.L., Mojtaba Aslami, Negrozov O.A.** Modified Wavelet-based Multilevel Discrete-Continual Finite Element Method for Local Structural Analysis. Part 2: Reduced Formulations of the Problems in Haar Basis. // Applied Mechanics and Materials, 2014, Vols. 670–671, pp. 724–727.
39. **Akimov P.A., Mozgaleva M.L., Mojtaba Aslami, Negrozov O.A.** Wavelet-Based Discrete-Continual Finite Element Method of Local Structural Analysis for Two-Dimensional Problems. // Procedia Engineering, 2014, Vol. 91, pp. 8–13.
40. **Mozgaleva M.L., Akimov P.A.** About Verification of Wavelet-Based Discrete-Continual Finite Element Method for Three-Dimensional Problems of Structural Analysis. Part 1: Structures with Constant Physical and Geometrical Parameters Along Basic Direction. // Applied Mechanics and Materials, 2015, Vol. 709, pp. 105–108.
41. **Mozgaleva M.L., Akimov P.A.** About Verification of Wavelet-Based Discrete-Continual Finite Element Method for Three-Dimensional Problems of Structural Analysis. Part 2: Structures with Piecewise Constant Physical and Geometrical Parameters Along Basic Direction. // Applied Mechanics and Materials, 2015, Vol. 709, pp. 109–112.
42. **Akimov P.A., Mozgaleva M.L.** Method of Extended Domain and General Principles of

Mesh Approximation for Boundary Problems of Structural Analysis. // Applied Mechanics and Materials, 2014, Vols. 580–583, pp. 2898–2902.

СПИСОК ЛИТЕРАТУРЫ

1. **Akimov P.A., Mozgaleva M.L., Kaytukov T.B.** Numerical solution of the problem of beam analysis with the use of B-spline finite element method. // International Journal for Computational Civil and Structural Engineering, 2020, Vol. 16, Issue 3, pp. 12–22.
2. **Li B., Chen X.** Wavelet-based numerical analysis: A review and classification. // Finite Elements in Analysis and Design, 2014, Vol. 81, pp. 14–31.
3. **Daubechies I.** Orthonormal bases of compactly supported wavelets. // Commun. Pure Appl. Math., 1988, Vol. 41, pp. 909–996.
4. **Li B., Cao H.R., He Z.J.** The construction of one-dimensional Daubechies wavelet-based finite elements for structural response analysis. // J. Vibroeng, 2011, vol. 13, pp. 729–738.
5. **Ma J.R., Xue J.J.** A study of the construction and application of a Daubechies wave-let-based beam element. // Finite Elements in Analysis and Design, 2003, Vol. 39, pp. 965–975.
6. **Mozgaleva M.L., Akimov P.A., Kaytukov T.B.** About wavelet-based computational beam analysis with the use of Daubechies scaling functions. // International Journal for Computational Civil and Structural Engineering, 2019, Vol. 15, Issue 2, pp. 95–110.
7. **Mozgaleva M.L., Akimov P.A., Kaytukov T.B.** Wavelet-based discrete-continual finite element plate analysis with the use of Daubechies scaling functions. // International Journal for Computational Civil and Structural Engineering, 2019, Vol. 15, Issue 3, pp. 96–108.
8. **Antes H.** Bicubic fundamental splines in plate bending. // Int. J. Numer. Methods Eng., 1974, Vol. 8, pp. 503–511.
9. **Han J.G., Ren W.X., Huang Y.** A spline wavelet finite-element method in structural mechanics. // Int. J. Numer. Methods Eng., 2006, Vol. 66, pp. 166–190.
10. **Han J.G., Ren W.X., Huang Y.** A spline wavelet finite element formulation of thin plate bending. // Eng. Comput., 2009, Vol. 25, pp. 319–326.
11. **Xiang J.W., Chen X.F., He Z.J., Zhang Y.H.** A new wavelet-based thin plate element using B-spline wavelet on the interval. // Comput. Math., 2008, Vol. 41, pp. 243–255.
12. **Chen X.F., Xiang J.W., Li B., He Z.J.** A study of multiscale wavelet-based elements for adaptive finite element analysis. // Adv. Eng. Softw., 2010, Vol. 41, pp. 196–205.
13. **Zhong Y.T., Xiang J.W.** Construction of wavelet-based elements for static and stability analysis of elastic problems. // Acta Mech. Solida Sin., 2011, Vol. 24, pp. 355–364.
14. **Yang Z.B., Chen X.F., Li B., He Z.J., Miao H.H.** Vibration analysis of curved shell using b-spline wavelet on the interval (BSWI). // Finite Elements Method and General Shell Theory, CMES85, 2012, pp. 129–155.
15. **Yang Z.B., Chen X.F., Zhang X.W., He Z.J**. Free vibration and buckling analysis of plates using B-spline wavelet on the interval Mindlin element. // Appl. Math. Model., 2013, Vol. 37, pp. 3449–3466.
16. **Xiang J.W., Chen X.F., Li B., He Y.M., He Z.J.** Identification of a crack in a beam based on the finite element method of a B-spline wavelet on the interval. // J. Sound Vibr., 2006, Vol. 296, pp. 1046–1052.
17. **Xiang J.W., Chen X.F., Mo Q.M., He Z.H.** Identification of crack in a rotor system based on wavelet finite element method. // Finite Elem. Anal. Des., 2007, Vol. 43, pp. 1068–1081.
18. **Xiang J.W., Liang M.** A two-step approach to multi-damage detection for plate structures. // Eng. Fract. Mech., 2012, Vol. 91, pp. 73–86.
19. **Xiang J.W., Matsumoto T., Long J.Q., Ma G**. Identification of damage locations based on operating deflection shape. // Nondestruct. Test. Eval., 2012, Vol. 1, pp. 1–15.

20. **Xiang J.W., Liang M.** Wavelet-based detection of beam cracks using modal shape and frequency measurements. // Comput.-Aided Civil Infrastruct. Eng., 2012, Vol. 27, pp. 439–454.
21. **Xiang J.W., Matsumoto T., Wang Y.W., Jiang Z.S.** Detect damages in conical shells using curvature mode shape and wavelet finite element method. // Int. J. Mech. Sci., 2013, Vol. 66, pp. 83–93.
22. **Dong H.B., Chen X.F., Li B., Qi K.Y., He Z.J.** Rotor crack detection based on high-precision modal parameter identification method and wavelet finite element model. // Mech. Syst. Signal Process., 2009, Vol. 23, pp. 869–883.
23. **Chen X.F., Yang Z.B., Zhang X.W., He Z.J.** Modeling of wave propagation in one-dimension structures using B-spline wavelet on interval finite element. // Finite Elem. Anal. Des., 2012, Vol. 51, pp. 1–9.
24. **Han J.G., Ren W.X., Huang Y.** A multivariable wavelet-based finite element method and its application to thick plates. // Finite Elem. Anal. Des., 2005, Vol. 41, pp. 821–833.
25. **Zhang X.W., Chen X.F., He Z.J.** The analysis of shallow shells based on multivariable wavelet finite element method. // Acta Mech. Solida Sin., 2011, Vol. 24, pp. 450–460.
26. **Han J.G., Ren W.X., Huang Y.** A wavelet-based stochastic finite element method of thin plate bending. // Appl. Math. Model., 2007, Vol. 31, pp. 181–193.
27. **Pian T.H.H., Chen D.P.** Alternative ways for formulation of hybrid stress elements. // Int. J. Numer. Methods Eng., 1982, Vol. 18, pp. 1679–1684.
28. **Pian T.H.H., Sumihara K.** Rational approach for assumed stress finite elements. // Int. J. Numer. Methods Eng., 1984, Vol. 20, pp. 1685–1695.
29. **Mau S.T., Tong P., Pian T.H.H.** Finite element solutions for laminated thick plates. // J. Compos. Mater., 1972, Vol. 6, pp. 304–311.
30. **Akimov P.A.** Correct Discrete-Continual Finite Element Method of Structural Analysis Based on Precise Analytical Solutions of Resulting Multipoint Boundary Problems for Systems of Ordinary Differential Equations. // Applied Mechanics and Materials, 2012, Vols. 204–208, pp. 4502–4505.
31. **Akimov P.A., Belostotskiy A.M., Mozgaleva M.L., Mojtaba Aslami, Negrozov O.A.** Correct Multilevel Discrete-Continual Finite Element Method of Structural Analysis. // Advanced Materials Research, 2014, Vol. 1040, pp. 664–669.
32. **Zolotov A.B., Akimov P.A.** Semianalytical Finite Element Method for Two-dimensional and Three-dimensional Problems of Structural Analysis. // Proceedings of the International Symposium LSCE 2002 organized by Polish Chapter of IASS, Warsaw, Poland, 2002, pp. 431–440.
33. **Akimov P.A., Sidorov V.N.** Correct Method of Analytical Solution of Multipoint Boundary Problems of Structural Analysis for Systems of Ordinary Differential Equations with Piecewise Constant Coefficients. // Advanced Materials Research, 2011, Vols. 250–253, pp. 3652–3655.
34. **Akimov P.A., Mozgaleva M.L.** Correct Wavelet-based Multilevel Discrete-Continual Methods for Local Solution of Boundary Problems of Structural Analysis. // Applied Mechanics and Materials, 2013, Vols. 353–356, pp. 3224–3227.
35. **Akimov P.A., Mozgaleva M.L.** Wavelet-based Multilevel Discrete-Continual Finite Element Method for Local Deep Beam Analysis. // Applied Mechanics and Materials, 2013, Vols. 405–408, pp. 3165–3168.
36. **Akimov P.A., Mozgaleva M.L.** Wavelet-based Multilevel Discrete-Continual Finite Element Method for Local Plate Analysis. // Applied Mechanics and Materials, 2013, Vols. 351–352, pp. 13–16.
37. **Akimov P.A., Mozgaleva M.L., Mojtaba Aslami, Negrozov O.A.** Modified Wavelet-based Multilevel Discrete-Continual Finite Element Method for Local Structural Analysis. Part 1: Continual and Discrete-Continual Formulations of the Problems. // Applied Mechanics and Materials, 2014, Vols. 670–671, pp.720–723.

38. **Akimov P.A., Mozgaleva M.L., Mojtaba Aslami, Negrozov O.A.** Modified Wavelet-based Multilevel Discrete-Continual Finite Element Method for Local Structural Analysis. Part 2: Reduced Formulations of the Problems in Haar Basis. // Applied Mechanics and Materials, 2014, Vols. 670–671, pp. 724–727.
39. **Akimov P.A., Mozgaleva M.L., Mojtaba Aslami, Negrozov O.A.** Wavelet-Based Discrete-Continual Finite Element Method of Local Structural Analysis for Two-Dimensional Problems. // Procedia Engineering, 2014, Vol. 91, pp. 8–13.
40. **Mozgaleva M.L., Akimov P.A.** About Verification of Wavelet-Based Discrete-Continual Finite Element Method for Three-Dimensional Problems of Structural Analysis. Part 1: Structures with Constant Physical and Geometrical Parameters Along Basic Direction. // Applied Mechanics and Materials, 2015, Vol. 709, pp. 105–108.
41. **Mozgaleva M.L., Akimov P.A.** About Verification of Wavelet-Based Discrete-Continual Finite Element Method for Three-Dimensional Problems of Structural Analysis. Part 2: Structures with Piecewise Constant Physical and Geometrical Parameters Along Basic Direction. // Applied Mechanics and Materials, 2015, Vol. 709, pp. 109–112.
42. **Akimov P.A., Mozgaleva M.L.** Method of Extended Domain and General Principles of Mesh Approximation for Boundary Problems of Structural Analysis. // Applied Mechanics and Materials, 2014, Vols. 580–583, pp. 2898–2902.

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SIMULATION OF A MULTI-FREQUENCY STOCKBRIDGE VIBRATION DAMPER OSCILATIONS WITH ENERGY SCATTERING HYSTERESIS

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Abstract: Spatial vibrations of a system containing a cable and a mass (solid body of arbitrary spatial configuration) are modeled. The problem is solved in a geometrically linear formulation, taking into account the hysteresis of energy scattering that is based on the kinematic equation. Identification of its parameters is carried out on the basis of experimental data on hysteresis loops of the limit cycle.

Keywords: vibration damper, frequencies, waveforms, non-stationary oscillations, hysteresis, kinematic approach

О МОДЕЛИРОВАНИИ КОЛЕБАНИЙ МНОГОЧАСТОТНОГО ГАСИТЕЛЯ ВИБРАЦИИ СТОКБРИДЖА С УЧЁТОМ ГИСТЕРЕЗИСА ЭНЕРГОРАССЕЯНИЯ

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Аннотация: Моделируются пространственные колебания системы, состоящей из тросика и груза – твёрдого тела произвольной пространственной конфигурации. Задача решается в геометрически линейной постановке с учётом гистерезиса энергорассеяния на основе кинематического уравнения, идентификация параметров которого осуществляется по экспериментальных данных о гистерезисных петлях предельного цикла.

Ключевые слова: гаситель вибрации, частоты и формы колебаний, нестационарные колебания, гистерезис, кинематический подход

INTRODUCTION

Vibration protection of wires, lightning cables, fiber-optic communication cables in systems of overhead power lines (OL) is carried out by various methods. The main of them is protection with the help of multi-frequency vibration dampers, which are structurally similar to the Stockbridge ones [1-3]. The typical design of such a damper consists of two mass connected by cables (flexible elements) with a clip that is rigidly fastened to the OL wire using a plate (Figure 1). The masses are located on different sides relative to the vertical axis of the clamp, in general, at different distances. The energy dissipation of vibrations occurs as a result of the mutual friction of the wire spirals from which the cable is made.

Experimental studies of the energy scattering of OL wires vibration dampers currently play a key role in the analysis of their effectiveness. However, it is important to create mathematical models of vibrations that allow not only to calculate the dynamic properties of dampers, but also to optimize their design parameters in order to increase the dissipation of vibration energy in the widest frequency range.

Figure 1. Vibration dampers conductors of OL

Energy dissipation occurs in the cable of the damper due to the elastic-plastic interaction of the wire spirals during their mutual friction. At the same time, as experiments show, the dependences of force factors on the corresponding kinematic parameters have a pronounced hysteresis character.

In this paper, we propose a kinematic model for describing hysteresis [4–6], according to which the bending and torsional momenta and their corresponding curvatures are connected by a special first-order differential equation, the coefficients of which are determined from experimental values for the limit cycle loop. In this case, one equation can describe an infinite set of similar trajectories, each of which is uniquely determined by the position of the initial point in the deformation diagram inside the limit cycle. The similarity of these curves is determined by their asymptotic approximation to the limit cycle curve. This model leads to a natural definition of the hysteresis cycle "orbital" under external non-stationary action on the damper.

BASIC KINEMATIC RELATIONS

Spatial vibrations of a system containing a cable and a mass (solid body of arbitrary spatial configuration) are considered. It is considered that one end of the cable is cantilevered, and the other is rigidly tethered to the mass. The gravitational load on the system is not taken into account. The cable axis is considered straight in the initial state.

A local trihedron of axes $O'x'y'z'$ is associated with the mass, which oscillates with the mass relative to a fixed coordinate system $Oxyz$. The pole O' is aligned with intersection of the cable axis and the surface of the mass in the place of their rigid fastening.

A rod model is taken for a cable, assuming that its cross-sections are displaced in space as rigid non-deformable disks.

The oscillations are considered small, allowing one to represent the movements of the cross-section points of the cable with the coordinate in the form

$$\begin{aligned} u(x,y,z) &= u_0(x) + \theta_2(x)z - \theta_3(x)y, \\ v(x,y,z) &= v_0(x) - \theta_1(x)z, \\ w(x,y,z) &= w_0(x) + \theta_1(x)y, \end{aligned} \tag{1}$$

Here u_0, v_0, w_0 are displacements of the cross-section pole; θ_1, θ_2, θ_3 are rotation angles of the cross-section relative to the axes x, y, z, respectively.

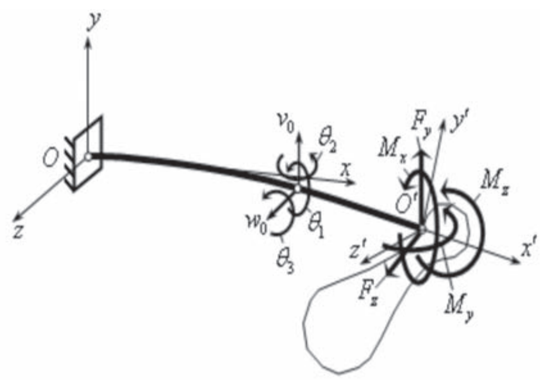

Figure 2. Coordinate axes, kinematic and power parameters of the "cable-weight" system

System “cable-weight” and the related coordinate frame are shown in Figure 2. Here the positive directions of the displacements and rotation angles of an arbitrary section of the cable are also shown, as well as forces and moments acting on the cable and mass at the point of their contact.

ELASTIC DEFORMATION RELATIONS

Formulae (1) allow us to obtain the following expressions for strains:

$$\varepsilon_x = \frac{\partial u}{\partial x} = u_0' + \theta_2'(x)z - \theta_3'(x)y,$$
$$\varepsilon_y = \frac{\partial v}{\partial y = 0}, \varepsilon_z = \frac{\partial w}{\partial z} = 0,$$
$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = -\theta_3 + v_0' - \theta_1' z,$$
$$\gamma_{xz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} = \theta_2 + w_0' + \theta_1' y.$$

Here and further, the strokes denote the derivatives of the values in the direction of x, except for the notation for the moving coordinate system $O'x'y'z'$. The relationship between stresses and strains is assumed in the form of Hooke's law using some reduced elastic E and shear modulus G. Then the axial stress $\sigma_x = E\varepsilon_x$, determines the axial force

$$N = \int_F \sigma_x \, dF = EF(u_0 - y_C\theta_3 + z_C\theta_2)' \quad (2)$$

and bending moments

$$M_z = -\int_F y\sigma_x dF = E\big(-y_C F u_0 + +J_z\theta_3 - J_{yz}\theta_2\big)', \quad (3)$$
$$M_y = \int_F z\sigma_x dF = E\big(z_C F u_0 - J_{yz}\theta_3 + J_y\theta_2\big)',$$

where y_C, z_C are the coordinates of the center of mass of the section relative to its pole.
Tangential stresses

$$\tau_{xy} = G\gamma_{xy}, \ \tau_{xz} = G\gamma_{xz}$$

determine the transverse forces

$$Q_y = \int_{Fcy} \tau_{xy} dF = = GF_{cy}\big[-\theta_3 + (v_0 - z_g\theta_1)'\big], \quad (4)$$
$$Q_z = \int_{Fcz} \tau_{xz} dF = GF_{cz}\big[\theta_2 + (w_0 + y_g\theta_1)'\big],$$

as well as the torque

$$M_k = \int_{Fcy} \tau_{xy} y dF - \int_{Fcz} \tau_{xz} z dF = = GJ_k\theta_1{}' + GF_{cz}y_g\big(\theta_2 + w_0'\big) + +GF_{cy}z_g\big(\theta_3 - v_0'\big), \quad (5)$$

where y_g, z_g are the coordinates of the section stiffness center relative to its pole; F_{cy}, F_{cz} are equivalent cross-sectional areas working for a shift in the direction of transverse forces Q_y and Q_z;

$$J_k = \int_{Fcz} y^2 \, dF + \int_{Fcy} z^2 \, dF$$

The axes x, y, z will be considered below as the principal and central ones for the cable sections. Then (2)-(5) are simplified:

$$N = EFu_0' \quad (6)$$
$$M_z = EJ_z\theta_3', M_y = EJ_y\theta_2' \quad (7)$$
$$Q_y = GF_{cy}\big(-\theta_3 + v_0'\big), Q_z = = GF_{cz}\big(\theta_2 + w_0'\big) \quad (8)$$
$$M_k = GJ_k\theta_1{}' \quad (9)$$

Formulas (6)-(9) are accepted as basic physical relations, where the EF tensile-compressive, EJ_z, EJ_y flexural, GF_{cy}, GF_{cz} shear and GJ_k torsional stiffnesses can be calculated analytically by formulae that take into account the internal structure of the cable [7-9], or by formulae obtained experimentally [10].

THE PROBLEM OF THE SYSTEM NATURAL OSCILLATIONS

According to the D'Alembert-Lagrange principle, the variation of the total energy of the system is represented as

$$\delta Э = \delta U - \delta A_p - \delta A_i = 0. \tag{10}$$

Here δU is the variation of the cable deformation potential energy: δA_p , δA – variations of the external and inertial forces work:

$$\delta A_p = \int_S p \cdot \delta u dS$$

$$\delta A_i = -\int_V \rho \ddot{u} \cdot \delta u dV$$

where u is the displacement vector of the body point, p is the load acting on the surface S; finally, ρ, V are the density and volume of the body.

In problems of natural oscillations

$$\delta A_p = 0.$$

The dynamic equations following from (10) have the form of Euler-Lagrange equation, and their natural boundary conditions appear.

High-frequency lateral vibrations are neglected below, since the damper is designed to suppress only low-frequency transverse vibrations. To simplify the problem, we will also neglect the shears strains using the relations

$$\theta_2 = -w_0', \theta_3 = v_0'.$$

It is also considered that the bending stiffness is

$$EJ_y = EJ_z = EJ ,$$

the section moments of inertia are

$$I_y = I_z = I ,$$

and the polar moment of inertia is denoted by

$$I_x = I_p .$$

Thus, the equations of vibrations after the exclusion of transverse forces are written in the form (11)

$$\begin{aligned} &EJv_0^{IV} - I\ddot{v}_0'' + m\ddot{v}_0 = 0,\\ &EJw_0^{IV} + I\ddot{w}_0'' + m\ddot{w}_0 = 0,\\ &-GJ_k\theta_1'' + I_p\ddot{\theta}_1 = 0. \end{aligned} \tag{11}$$

The boundary conditions at $x = l$ take the form

$$\begin{aligned} &Q_y(l) + M^{(г)}\Big[\ddot{v}_0(l) + x_C^{(г)}\ddot{\theta}_3(l) -\\ &-z_C^{(г)}\ddot{\theta}_1(l)\Big] = 0,\\ &Q_z(l) + M^{(г)}\Big[\ddot{w}_0(l) - x_C^{(г)}\ddot{\theta}_2(l) +\\ &+y_C^{(г)}\ddot{\theta}_1(l)\Big] = 0,\\ &M_k(l) + M^{(г)}\Big[-z_C^{(г)}\ddot{v}_0(l) + y_C^{(г)}\ddot{w}_0(l)\Big] +\\ &+I_{xx}^{(г)}\ddot{\theta}_1 - I_{xy}^{(г)}\ddot{\theta}_2 - I_{xz}^{(г)}\ddot{\theta}_3 = 0,\\ &M_y(l) - M^{(г)}x_C^{(г)}\ddot{w}_0(l) - I_{xy}^{(г)}\ddot{\theta}_1 + I_{yy}^{(г)}\ddot{\theta}_2 -\\ &-I_{yz}^{(г)}\ddot{\theta}_3 = 0,\\ &M_z(l) + M^{(г)}x_C^{(г)}\ddot{v}_0(l) - I_{xz}^{(г)}\ddot{\theta}_1 - I_{yz}^{(г)}\ddot{\theta}_2 +\\ &+I_{zz}^{(г)}\ddot{\theta}_3 = 0. \end{aligned} \tag{12}$$

where $M^{(г)}$ is the mass of the load; $x_C^{(г)}, y_C^{(г)}, z_C^{(г)}$ and $I_{ij}^{(г)}(i,j = x,y)$ are the coordinates of the mass gravity center and its moments of inertia relative to the trihedron of the moving axes $O'x'y'z'$.

The solution of (11) are:

$$\begin{aligned} &v_0 = \sin\omega t(A_1 \sin a x +\\ &+A_2 \cos a x + A_3 shbx + A_4 \mathrm{ch}bx),\\ &w_0 = \sin\omega t(B_1 \sin a x +\\ &+B_2 \cos a x + B_3 shbx + B_4 \mathrm{ch}bx),\\ &\theta_1 = \sin\omega t(D_1 \sin k x + D_2 \cos k x), \end{aligned}$$

where $A_{1,2,3,4}$, $B_{1,2,3,4}$, $D_{1,2}$ are the constants of integration, $\omega = \omega_i$ (i = 1, 2, ...) are the natural frequencies;

$$\begin{aligned} &a^2 = \frac{1}{2EJ}\left(\omega^2 I + \omega\sqrt{\omega^2 I^2 + 4EJm}\right),\\ &b^2 = \frac{1}{2EJ}\left(-\omega^2 I + \omega\sqrt{\omega^2 I^2 + 4EJm}\right);\\ &k^2 = \omega^2 \frac{I_p}{GJ_k}. \end{aligned}$$

Taking into account the console pinning at $x = 0$, the solution takes the form

$$\begin{aligned} &v_0 = \sin\omega t(A_1\varphi_1 + A_2\varphi_2), w_0 =\\ &\sin\omega t(B_1\varphi_1 + B_2\varphi_2),\\ &\theta_1 = D \sin\omega t \sin k x, \end{aligned} \tag{13}$$

where we have the eigenforms:

$$\begin{aligned} &\varphi_1(x) = \mathrm{sh}bx - \frac{b}{a}\cdot \sin a x, \varphi_2(x) = \mathrm{ch}bx -\\ &-\cos a x \end{aligned} \tag{14}$$

The constants $A_{1,2}$, $B_{1,2}$ and D are found from the boundary conditions (23) at x = 1. Substituting (13), (14) into (12) leads to a homogeneous system of five equations with respect to the required five constants. The equality of determinant to zero is the nontriviality condition of the system solution

$$\Delta(\omega) = 0 \,, \tag{15}$$

the roots of which are the frequencies of the system natural oscillations:

$$\omega_i \,, \; i = 1, 2, \dots \,.$$

The search for the transcendental equation roots (15) of a very complex structure can be carried out by a step-by-step method, changing the frequency ω with some small step $\Delta\omega$ from zero to some selected value. When changing the sign of the determinant, some numerical method is used, for example, the method of dividing in half.

DESCRIPTION OF THE NON-STATIONARY PROCESS HYSTERESIS

To describe the hysteresis under the conditions of nonstationary oscillations, we propose an ordinary differential equation of the first order [4-6] with the right-hand side of the form

$$\frac{dM}{d\kappa} = \sum_{i=1}^{k} \sum_{j=1}^{m} C_{ij} \kappa^{i-1} M^{j-1} \tag{16}$$

where κ is the bending curvature of the cable, M is the bending moment; C_{ij} are the coefficients determined by approximation methods, minimizing the discrepancy of the analytical representation $\frac{dM}{d\kappa}$ (16) to the experimental data describing the limit cycle.

It is assumed that all possible hysteresis trajectories – dependences $M(\kappa)$ lie within the limit cycle, i.e., the region bounded by curves $M(\kappa)$ corresponding to the maximum ranges of curvature and moment changes. The numbers k and m are selected as a result of simple numerical tests. The values of these parameters determine the character (speed) of the asymptotic approximation of the solution with the initial point (κ_0, M_0) inside the domain to the limit cycle curves.

The values C_{ij} can be calculated using the least squares method, for instance.

An example of the dependencies $M(\kappa)$ obtained experimentally in [11] is given in Figure 3. The bold lines correspond to the limit cycle. The thin lines correspond to possible loop-like trajectories within the limit cycle region. Trajectories for which the curvature increases with increasing moment correspond to the process of “loading”. Conversely, trajectories for which the curvature decreases as the moment decreases correspond to the “unloading” process. The beginning of the process is determined by some point inside the limit cycle area.

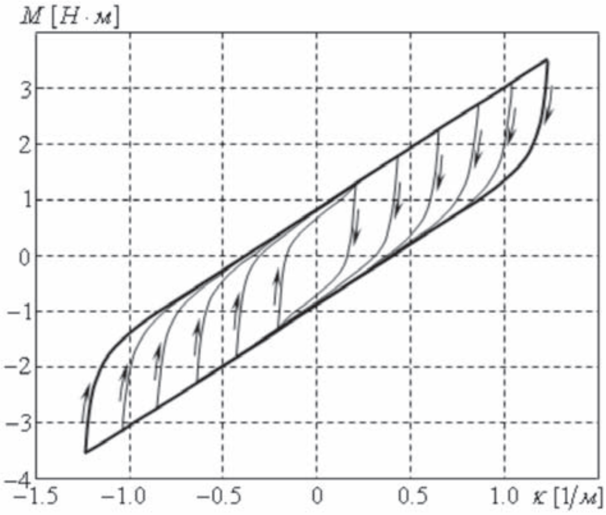

Figure 3. Hysteresis trajectories. “Loading” processes are marked with up arrows, “unloading” – with down arrows. Bold curves limit the area of the limit cycle. Thin-define possible trajectories of intermediate States

Next, the following notation is introduced:

$$\kappa_y = -w_0'', \kappa_y = -w_0'', \, \kappa_k = \theta_1{}'.$$

Based on (16) and the introduced curvature notation

$$\frac{dM_y}{d\kappa_y} = \Phi_y, \frac{dM_z}{d\kappa_z} = \Phi_z, \frac{dM_k}{d\kappa_k} = \Psi, \quad (17)$$

Where

$$\Phi_y = \sum_{i=1}^{k}\sum_{j=1}^{m}(-1)^{i-1}C_{ij}\left(w_0''\right)M_y^{j-1},$$
$$\Phi_z = \sum_{i=1}^{k}\sum_{j=1}^{m} C_{ij}\left(v_0''\right)M_z^{j-1}, \quad (18)$$
$$\Psi = \sum_{i=1}^{k}\sum_{j=1}^{m} D_{ij}\left(\theta_1'\right)^{i-1}M_k^{j-1}.$$

The equations follow from (17)

$$\dot{M}_y = -\dot{w}_0''\Phi_y,$$
$$\dot{M}_z = \dot{v}_0''\Phi_z, \quad (19)$$
$$\dot{M}_z = \dot{\theta}_1'\Psi,$$

that must be integrated together with the equations of forced oscillations in the form:

$$M_z'' - I\ddot{v}_0'' + m\ddot{v}_0 = f_y;$$
$$-M_y'' + I\ddot{w}_0'' + m\ddot{w}_0 = f_z; \quad (20)$$
$$-M_1' + I_p\ddot{\theta}_1 = f_k.$$

Here, $f_y(t, x)$, $f_z(t, x)$ and $f_k(t, x)$ is the specified external distributed load.

The unknowns of the system (19), (20) are v_0, w_0, θ_1, M_y, M_z, M_k.

The solution is constructed using the expansion with respect to the eigenforms of vibrations of the undamped system:

$$v_0(t,x) = \sum_{i=0}^{r}\alpha_i(t)V_i(x),\ w_0(t,x) = \sum_{i=0}^{r}\beta_i(t)W_i(x),$$
$$\theta_1(t,x) = \sum_{i=0}^{r}\gamma_i(t)\Theta_i(x),$$
$$M_y(t,x) = \sum_{i=0}^{r}\mu_i(t)W_i''(x),\ M_z(t,x) = \sum_{i=0}^{r}\nu_i(t)V_i''(x), \quad (21)$$
$$M_k(t,x) = \sum_{i=0}^{r}\eta_i(t)\Theta_i'(x),$$

where the waveforms (22)

$$V_i(x) = A_{1i}\varphi_{1i}(x) + A_{2i}\varphi_{2i}(x), W_i(x) = B_{1i}\varphi_{1i}(x) + B_{2i}\varphi_{2i}(x), \quad (22)$$
$$\Theta_i(x) = D_i \sin k_i x$$

are determined from the solution of the spectral problem; index i is the number of natural frequency of vibrations; r is the number of considered natural forms of vibrations; the value $i = 0$ corresponds to the unit forms that determine the motion of the system as a solid. The functions $\alpha_i(t)$, $\beta_i(t)$, $\gamma_i(t)$, $\mu_i(t)$, $\nu_i(t)$, $\eta_i(t)$ are to be defined. Substituting (21) with (22) in (19), (20) leads to a system of equations

$$\sum_{i=0}^{r}\left(\dot{\mu}_i W_i'' + \dot{\beta}_i\Phi_y W_i''\right) = 0,$$
$$\sum_{i=0}^{r}\left(\dot{\nu}_i V_i'' - \dot{\alpha}_i\Phi_z V_i''\right) = 0,\ \sum_{i=0}^{r}\left(\dot{\eta}_i\Theta_i' - \dot{\gamma}_i\Psi\Theta_i'\right) = 0, \quad (23)$$
$$\sum_{i=0}^{r}\left[\ddot{\alpha}_i\left(mV_i - IV_i''\right) + \nu_i V_i^{IV}\right] = f_y,$$
$$\sum_{i=0}^{r}\left[\ddot{\beta}_i\left(mW_i - IW_i''\right) - \mu_i W_i^{IV}\right] = f_z,$$
$$\sum_{i=0}^{r}\left(\ddot{\gamma}_i I_p\Theta_i - \eta_i\Theta_i''\right) = f_k.$$

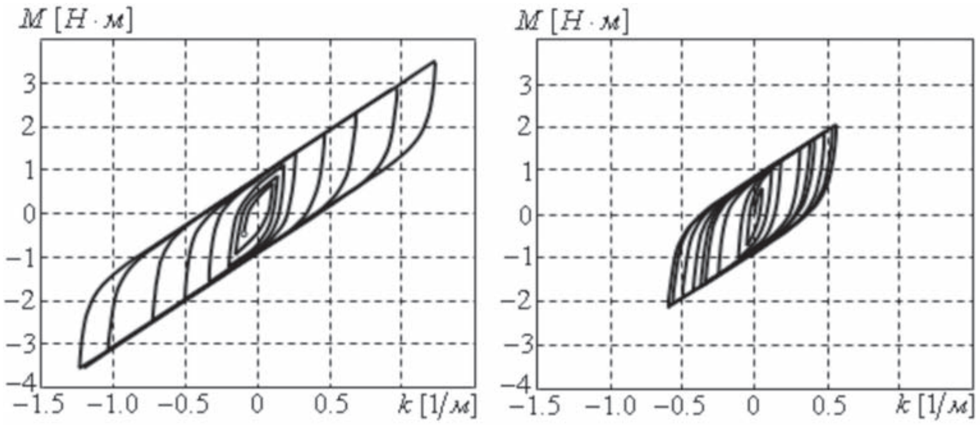

Figure 4. Characteristic hysteresis loops under different initial conditions and external excitation

Sequential multiplication of the (23) by the corresponding oscillation forms V_m, W_m, Θ_m (m = 1, ..., r) and integration along the length of the cable leads to the initial problem for the system of ordinary differential equations with respect to относительно $\alpha_i(t), \beta_i(t), \gamma_i(t), \mu_i(t), \nu_i(t), \eta_i(t)$. This system is integrated by numerical methods. Some characteristic hysteresis trajectories obtained as a result of solving the nonstationary equations (23) are shown in Figure 4.

CONCLUSIONS

In this paper, we propose an approach to solving problems of multi-frequency vibration dampers of OL wires non-stationary oscilations, taking into account the energy dissipation of the hysteresis type. To account for energy scattering, a phenomenological method based on the use of kinematic equations, the coefficients of which are determined from the analysis of experimental data for limit cycles, is proposed. This approach can be extended to the problems of non-stationary vibrations of other mechanical objects with a hysteresis character of energy scattering.

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REFERENCES

1. **Stockbridge G.H.** Vibration damper. U.S. Patent 1675391. Filling date: Nov 12, 1925. Issue date: Jul 3, 1928.
2. **McCombe J., Haigh F.R.** Overhead Line Practice (3rd ed.). Macdonald, 1966, pp. 216–219.
3. **Shkaptsov V.A.** Metodicheskie ukazanija po tipovoj zashhite ot vibracii i subkolebanij provodov i grozozashhitnyh trosov vozdushnyh linij jelektroperedachi naprjazheniem 35-750 kV [Methodical instructions on typical protection against vibration and sub-vibrations of wires and lightning protection cables of overhead power lines with voltage of 35–750 kV]. Moscow, SPO “ORGRES”, 1991, 68 pages (in Russian).
4. **Danilin A.N., Vinogradov A.A., Lilien J.-L.** A Kinematic Model for Hysteretic Dissipation of Vibration Energy for Torsional Damper and Detuner (TDD). Proc. of Seventh International Symposium on Cable Dynamics, Vienna (Austria), December 10–13, 2007, pp. 247–253.
5. **Danilin A.N., Shalashilin V.I.** Sposob identifikacii gisterezisa na primere gasitelja “pljaski provodov” [A method for identifying hysteresis on the example of a dampener “dances of wires”]. // Applied Mechanics, 2010, Vol. 46, No. 5, pp. 115–124 (in Russian).
6. **Danilin A.N., Kozlov K.S.** Modelirovanie kolebanij mnogochastotnogo gasitelja vibracii s uchetom gisterezisa dissipacii jenergii [Modeling of vibrations of a multi-frequency vibration damper taking into account the hysteresis of energy dissipation]. // Proceedings of the IX all-Russian scientific conference named after Yu.I. Neymark “Nonlinear oscillations of mechanical systems”. Nizhny Novgorod, September 24–29, 2012, pp. 320–329 (in Russian).
7. **Shalashilin V.I., Danilin A.N., Tsvetkov Yu.L., Ryzhov S.V.** Model' provoda vozdushnoj linii jelektroperedachi [Model of an overhead power line wire]. // Mechanics of composite materials and structures, 2005, Vol. 11, No. 4, pp. 564–572 (in Russian).
8. **Shalashilin V.I., Danilin A.N., Volkov-Bogorodskiy D.B.** Model of overhead line conductor with interaction of layers. // Proceedings of Sixth International Symposium on Cable Dynamics. Charleston, South Carolina (U.S.A.), Sept 19–22, 2005, pp. 371–377.
9. **Danilin A.N., Kuznetsova E.L., Rabinsky L.N., Tarasov S.S.** New model of deformation of wire systems of spiral structure. // Nonlinear world, 2011, Vol. 9, No. 10, pp. 635–645.
10. **Dubois H., Lilien J.L., Dal Maso F.** A new theory for frequencies computation of

overhead lines with bundle conductors. // Revue AIM (Belgium), 1991, No 1, pp. 45-62.
11. **Sauter D., Hagedorn P.** On the hysteresis of wire cables in stockbridge dampers. // Int. J. of Non-linear Mechanics, 2002, Vol. 37, No. 8, pp. 1453–1459.

СПИСОК ЛИТЕРАТУРЫ

1. **Stockbridge G.H.** Vibration damper. U.S. Patent 1675391. Filling date: Nov 12, 1925. Issue date: Jul 3, 1928.
2. **McCombe J., Haigh F.R.** Overhead Line Practice (3rd ed.). Macdonald, 1966, pp. 216–219.
3. **Шкапцов В.А.** Методические указания по типовой защите от вибрации и субколебаний проводов и грозозащитных тросов воздушных линий электропередачи напряжением 35–750 кВ. – М.: СПО ОРГРЭС, 1991. – 68 с.
4. **Danilin A.N., Vinogradov A.A., Lilien J.-L.** A Kinematic Model for Hysteretic Dissipation of Vibration Energy for Torsional Damper and Detuner (TDD). Proc. of Seventh International Symposium on Cable Dynamics, Vienna (Austria), December 10–13, 2007, pp. 247–253.
5. **Данилин А.Н., Шалашилин В.И.** Способ идентификации гистерезиса на примере гасителя «пляски проводов». // Прикладная механика, 2010, том 46, №5, с. 115–124.
6. **Данилин А.Н., Козлов К.С.** Моделирование колебаний многочастотного гасителя вибрации с учетом гистерезиса диссипации энергии. // Труды IX всероссийской научной конференции им. Ю.И. Неймарка «Нелинейные колебания механических систем». – Нижний Новгород, 24–29 сентября 2012 г. Нижний Новгород: Издательский дом «Наш дом», с. 320–329.
7. **Шалашилин В.И., Данилин А.Н., Цветков Ю.Л., Рыжов СВ.** Модель провода воздушной линии электропередачи. // Механика композиционных материалов и конструкций, 2005, том 11, №4, с. 564-572.
8. **Shalashilin V.I., Danilin A.N., Tsvetkov Yu.L., Ryzhov S.V.** Model of an overhead power line wire. // Mechanics of composite materials and structures, 2005, Vol. 11, No. 4, pp. 564–572.
9. **Shalashilin V.I., Danilin A.N., Volkov-Bogorodskiy D.B.** Model of overhead line conductor with interaction of layers. // Proceedings of Sixth International Symposium on Cable Dynamics. Charleston, South Carolina (U.S.A.), Sept 19–22, 2005, pp. 371–377.
10. **Danilin A.N., Kuznetsova E.L., Rabinsky L.N., Tarasov S.S.** New model of deformation of wire systems of spiral structure. // Nonlinear world, 2011, Vol. 9, No. 10, pp. 635–645.
11. **Dubois H., Lilien J.L., Dal Maso F.** A new theory for frequencies computation of overhead lines with bundle conductors. // Revue AIM (Belgium), 1991, No 1, pp. 45–62.
12. **Sauter D., Hagedorn P.** On the hysteresis of wire cables in stockbridge dampers. // Int. J. of Non-linear Mechanics, 2002, Vol. 37, No. 8, pp. 1453–1459.

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A CRACK DETECTION SYSTEM FOR STRUCTURAL HEALTH MONITORING AIDED BY A CONVOLUTIONAL NEURAL NETWORK AND MAPREDUCE FRAMEWORK

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Abstract: The quickly expanded development of artificial intelligence offers alternative ways to solve numerous civil engineering problems. The work is devoted to the development of a computer-vision-based crack detection system capable to process big data related to pathology recognition. In this study, we discuss an automated crack type classification pipeline based on CNN deep learning algorithm and MapReduce framework. The results of numerical modeling illustrate the potential of the crack detection system.

Keywords: deep learning, ground truth segmentation, machine learning, structural health monitoring, crack detection, MapReduce

СИСТЕМА ОБНАРУЖЕНИЯ ТРЕЩИН ДЛЯ МОНИТОРИНГА СОСТОЯНИЯ КОНСТРУКЦИЙ С ПОМОЩЬЮ СВЕРТОЧНОЙ НЕЙРОННОЙ СЕТИ И ФРЕЙМВОРКА MAPREDUCE

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Аннотация: Быстрое развитие искусственного интеллекта предлагает альтернативные способы решения многочисленных проблем гражданского строительства. Работа посвящена разработке системы обнаружения трещин на основе компьютерного зрения, способной обрабатывать большие данные, связанные с распознаванием патологии. В этом исследовании мы обсудили конвейер автоматической классификации типов трещин, основанный на алгоритме глубокого обучения CNN и инфраструктуре MapReduce. Результаты численного моделирования иллюстрируют потенциальные возможности системы обнаружения трещин.

Ключевые слова: глубокое обучение, разметка достоверных данных, машинное обучение, мониторинг состояния конструкции, обнаружение трещин, MapReduce

1. INTRODUCTION

Thinking on the main principles of orthogenesis, taking into account that some "driving force" of evolutionary progress is always applied to reach a goal, it becomes obvious that the large-scale trends in massive digital transformation increase informational complexity. Started in the 2010th, the explosion of large volumes of structured and non-structured data production (text, image, video, and audio) initiated the so-called “fourth wave” of data evolution. Only several years later the “4th Industrial Revolution” stimulated the development of new industrial relations. That is to say, to stay on the market each company has to adapt in real-time available resources (technical or human) and solutions with respect to the shrinking technological innovation cycle. This makes "data"-related questions (format, quantity and quality, availability, time variation, etc.) highly important. Being influenced by technological progress, civil engineering adapts to the new environmental conditions. Many companies handle with cloud tools, storage cloud spaces, third-party calculations to speed up the project realization on all its life-stages with respect to technological innovations. Since no human and no "ordinary computer" can evaluate the millions of variables concerning a real-world phenomenon new AI-based raw data processing platforms and frameworks have to be developed.

The main streams of AI applications development concern the data either deterministic (all factors are known and controlled) or probabilistic (all factors have a probability to happen). To illustrate these last we limit examples to genetic algorithms, swarm intelligence, and artificial neural networks, which are considered as a core subset of machine learning (ML) techniques (see Table 1). As it is possible to admit, the mentioned methods can be grouped as modeling, optimization, control, or forecast and are related to all the life-stages of the construction process from the concept to maintenance and demolition. Despite the variety of the solutions, the expertise related tasks as structural damage detection (SDD) still have need of a human-specialist final decision. So, widely used visual, ultrasonic, or leak testing as well as acoustic emission, optical or laser methods can be augmented by ML technology, which in-depth development (mostly it is based on a statistical representation of a phenomenon under study) makes possible to automate most of these evaluations due to "deep feature extraction" and "feature classification" [12]. The choice of ML technology depends on the domain of application

Table 1. Some examples of AI techniques application in civil engineering

Technique	Method	Purpose	Application
Genetic algorithm (GA) [1–4]	• unsupervised and nonparametric • selective evolutionary • multi-objective fuzzy-genetic control	• to solve ill-posed large-scale optimization problem • to determine decision boundary • to monitor the over-time changes • to complete the sensitivity analysis	• structural damage detection • reduction of negative impact of environment on structures • shape and cross-section optimization of truss structures • cable tension changes control • vibration reduction • heat exchange
Swarm intelligence (SI) [5–9]	• particle swarm optimization • ant colony algorithm • bee colony algorithm • krill herd algorithm	• to solve global optimization problem in the hyper imensional space • to select reasonably design parameters • to update the dynamic models	• potential damage reduction (i.e. seismic safety of building, bridge vibrations) • slope stability analysis • optimal selection of geomechanical parameters • diverse design problems (tubular column, three-bar truss, helical compression string and etc.)
Artificial neural networks (ANN) [10–13]	• supervised • semi-supervised • non-supervised • reinforcement	• to solve highly complex ill-posed problems • to predict and forecast processes of different nature • to classify structural damages, predictive scoring, predictive maintenance • to detect abnormalities	• structural damage detection • reliability analysis • reduction of construction waste • structural optimization and control • health monitoring • damage detection

and of the area of engineering research. Let us consider the main advantages of ML-based SDD for some abstract civil construction.

The life cycle of any civil structure depends on cause-damage internal and external environmental factors (temperature, humidity, pressure, creep, corrosion, shrinkage, etc.). Therefore to prevent damages in the early stages, continuous evaluation of the structure is required. Despite the popularity, mostly referred to the surface inspection (fissures, cracks, leaks, etc.) the visual-based methods of damage detection become laborious and time-consuming for relatively large and complex structures demanding highly-skilled-trained experts. The main reasons are difficulties of access to certain parts of constructions as well as quantity and quality of structured and non-structured information to analyze.

Taking into account the progress being made in the field, the aim of this study is the development of an automated crack-detection system aided by a high-throughput deep learning algorithm for complex features extraction.

To reach the objective, we organize the work in the following manner. In Section 2, we analyze the existing ML-techniques based on computer vision and commonly used features for cracks detection. Section 3 deals with the methodological aspects of the cracks detection and classification system based on the semantic segmentation. Next, in Section 4, we evaluate the performances of the designed system and compare it with the other well-performed methods. Section 5 contains concluding remarks on advantages and limitations as well as recommendations for further development.

2. METHODS FOR DETECTING CRACKS

2.1. Cracks: naïve conception

Cracks and fissures refer to the phenomenon of the surface splitting without breaking it apart. Usually, they are observed as “lines” or “broken curves” of different width, length, and spatial orientation. Through empirical observation for specified surface (were-used materials, physical or chemical characteristics, a period of exploitation, environmental conditions, etc.), the reason of cracks appearance can be concluded. An introduction of cracks classification serves to estimate damage they would or already have caused. In this work, we would pass on only the principles of cracks detection. Hence the further considerations concern only concrete surfaces in the wide sense.

Figure 1. Some examples of the crack-damaged concrete surfaces

Table 2. Crack classification according opening (*a*, *b*, and *c* are the threshold values taken into account by an expert)

Severity class	Opening [mm]	Description
0	$< a$	out of consideration
1	$[a, b)$	an aesthetic nature
2	$[b, c)$	low risk of non-returnable surface damage
3	$\geq c$	elevated risk of non-returnable surface damage

To create an automated crack detection system, first, the classification criteria have to be settled, allowing experts to conclude on the damage state and to take the actions. Using visual analysis (see Fig. 1), cracks can be classified according to the *opening size* or *severity* (usually graduated measures in mm), to the *spatial orientation* (longitudinal, transversal, and miscellaneous), and to *expert-based characteristics* (plastic shrinkage, expansion, heaving, settling, overloading, crazing or crusting caused by premature drying, etc.). The diverse combinations of these features refer to multi-class classification problem, where classes and subclasses hierarchy has to be introduced by an expert with respect to the inspected structure. The example of the possible severity-based classification presents Table 2. As it is possible to notice this classification deal only with four levels of severity, other subdivision can be used without losing generalities.

We have also to admit that identification of spatial orientation as well as of expert-added characteristics depend on the architecture of the automated detection system and computer-vision techniques. Let us discuss some of them.

2.2. Computer-vision detection techniques

An automatic computer vision-based inspection of continuous surfaces (and, in a consequence, the defaults detection) supports a process of several stages, namely: image acquisition (surface lighting, camera configuration, synchronization, information storage), damage detection (preprocessing, localization, classification), and result exploitation (displaying and reporting information, decision making). The performance of the decision making depends on both hardware and software used in the detection system. It can be improved by increasing the quantity and quality of processed information subjected to decreasing processing time and controlling that repository of images fit in memory. In our opinion, the core element of the automatic damage detection system is the damage detection algorithm (see Fig. 2). Once its characteristics are available, the rest of the solution can be adapted for obtaining the desired parameters of the system as a whole.

The starting point of any damage detection algorithm supported by computer vision techniques is the digital image representation. The initial image is converted to a gray-scale one under selected resolution. Hence, the $n_1 - by - n_2$ pixels grayscale digital image corresponds to the surface associated with the bounded closed set

$$D = [0, n_1 - 1] \times [0, n_2 - 1] \subset R_+^2, \qquad (1)$$

where each pixel $(x, y) \in D$ is characterized by an intensity

$$f_{(x,y)} \in \mathsf{F},$$

where $\mathsf{F} = \{f_{\min}, ..., f_{\max}\} \subset \mathsf{R}_+$ is an ordered final set. Further, the values of intensities are sequentially transformed to find regions of suspected damage. The detection techniques, called the semantic segmentation, can be generalized as follows.

The fact that the pixel frequencies related to cracks are usually shifted to "black color," such that the surrounding neighborhood seems to be lighter, is used to detect edges of cracks. Therefore choosing some threshold value one can point out damages.

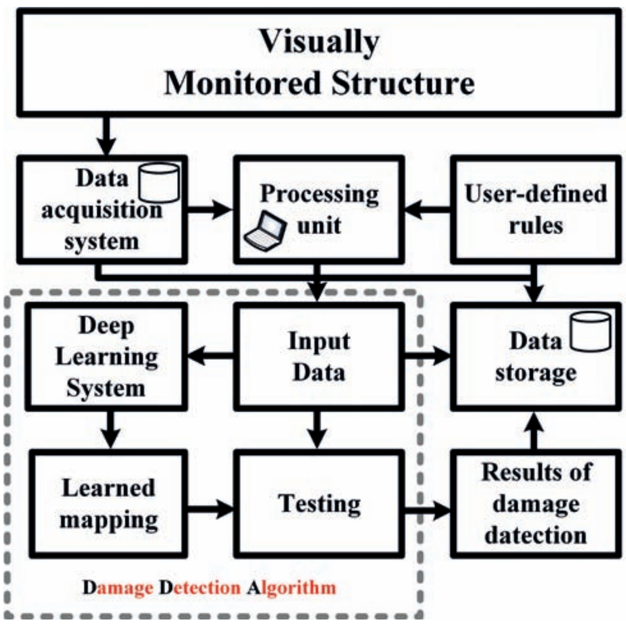

Figure 2. The scheme of the automatic damage detection system

However, if both regions have similar brightness, this kind of separation is hardly possible without additional pre-processed and post-processed transformations. This idea is supported by ML technique, which requires:

• preprocessing data (to eliminate anomalies related to acquisition system and to remove significant variations in initial intensities);
• segmentation (to detect desired features);
• classification (to group extracted features according to defined rules);
• post-processing (to refine the segmented and classified structures);
• evaluation (to analyze segmentation and classification quality).

As it is was indicated in [12–14], the accuracy of the damage detection algorithm mostly depends on strengths and weaknesses of the selected segmentation method (threshold-based, region-based, active contour model, mean-shift, K-means, Otsu, etc.). It can be significantly improved by deep learning methods using complex network architectures with significant volume of initial data. The CNN-based five-level architecture, developed in [13, 14] and called CrackNet, can be named as an example of automation of crack detection (see Fig. 3).

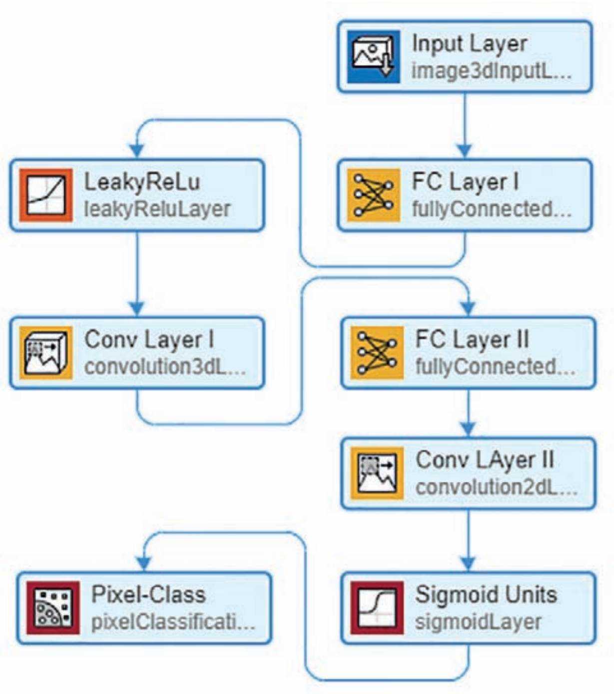

Figure 3. Sketch of overall architecture for crack detection – CrackNet [13]

To ensure desired pixel-wise accuracy authors had used more than million parameters. Despite the reduction of parameter space by introduction of more hidden layers, these methods are very time-consuming methods [15, 16].
To speed up the performances of the detection method some authors propose to treat the crack detection phase and crack characterization phase separately, reducing the number of processing operations (it can be done by Big Data technologies) and consistently getting rid of unnecessary information [17, 18].

3. RESEARCH METHODOLOGY

3.1. Method overview

The damage detection algorithm usually contains two stages:

• "*separation*", where regions of interest (ROI) are separated from the background, and
• "*classification*", where ROIs are subdivided into subsets according to some selected criteria.

Both stages refer to classification problems (binary and multi-class) and can be solved either by non-supervised or by supervised learning methods. In the case of supervised learning, the patterns to be recognized are compared with the labeled ones. In this work, we will apply the supervised methods to both stages each time solving the optimization tasks. Analysis of the patterns, where cracks were presented, shows that the damaged surface is much smaller than the background surface. This causes a problem of miss-balanced classification on the first stage and as a consequence miss-classification on the second one. To reduce miss-classification error a kind of regularization has been included to the optimization criteria.

Let I^{tag} be the labeled image, which corresponds to the image I defined by (1), where total number of pixels is $M = n_1 \cdot n_2$. We will call a pair (I, I^{tag}) as a training example. Labels of I^{tag} form M elements ground truth set T subdivided on K disjoint subsets T_k (classes). Each subset T_k, $k \in K$, contains m_k elements t_{kj}, $j = \{1, ..., m_k\}$, such that $\sum_k m_k = M$, $0 \le m_k \le M$. To compensate the influence of larger classes, each subset is weighted as

$$w_k = \frac{1}{(m_k)^2 + \varepsilon},$$

where ε is a compensation term settled as a machine precision value to avoid division by zero, if T_k is an empty set.

We denote the results of prediction for some possible segmentation $Q = \{Q_k, 1 \le k \le K\}$ of the initial image I by q_{kj}, $k = \{1, ..., K\}$, $j = \{1, ..., m_k\}$. The wise-element loss between one image I and the corresponding ground truth image I^{tag} can be measured by the generalized Dice loss function:

$$\mathrm{L}(q,t) = 1 - \frac{\left(2\sum_{k=1}^{K} w_k \sum_{j=1}^{m_k} q_{kj} t_{kj}\right) + \varepsilon}{\sum_{k=1}^{K} w_k \sum_{j=1}^{m_k} \left((q_{kj})^2 + (t_{kj})^2\right) + \varepsilon}, \quad (2)$$

where the ε term is used to avoid division by zero, if Q_k or T_k are empty sets.

Hence, the classification turns to the solution of the optimization problem:

$$\mathrm{J}\ (q,t) = \underset{q \in Q}{\arg\min}\, \mathrm{L}(q,t). \quad (3)$$

In the supervised learning, the problem (3) is repetitively solved N times on the set of training examples (I_{tr}, I_{tr}^{tag}):

$$\mathrm{J}^*(q,t) = \underset{\substack{q^{(i)} \in Q_{tr} \\ 1 \le i \le N}}{\arg\min} \frac{1}{N} \sum_{i=1}^{N} \mathrm{L}\left(q^{(i)}, t^{(i)}\right), \quad (4)$$

where the index "tr" stands for the training set. The same optimization criteria is applied in case of severity class outlining. The severity-class labels are determined according to the method proposed in [17]. The crack opening is calculated on pixel level as average width along the crack skeleton:

$$\bar{u} = \frac{u_{cr}}{u_{sk}} r_s, \quad (5)$$

where u_{cr} and u_{sk} are the numbers of pixels associated with the detected crack and its skeleton, whereas r_s is the spatial resolution of the acquisition device.

In both classification cases, the solution of (4) is considered as a predictive model. Once it have been evaluated on the validation set of examples (I_{val}, I_{val}^{tag}), each new image can be examined to determined damages. As it is possible to conclude, the crack detection and classification algorithm has two main phases: the training and the testing. The training phase requires the samples selection, preprocessing of initial data, the definition of the neural network architecture to create the predictive model. During testing phase the cracks are detected and classified, the results are evaluated by means of the performances metrics (see Fig. 4).

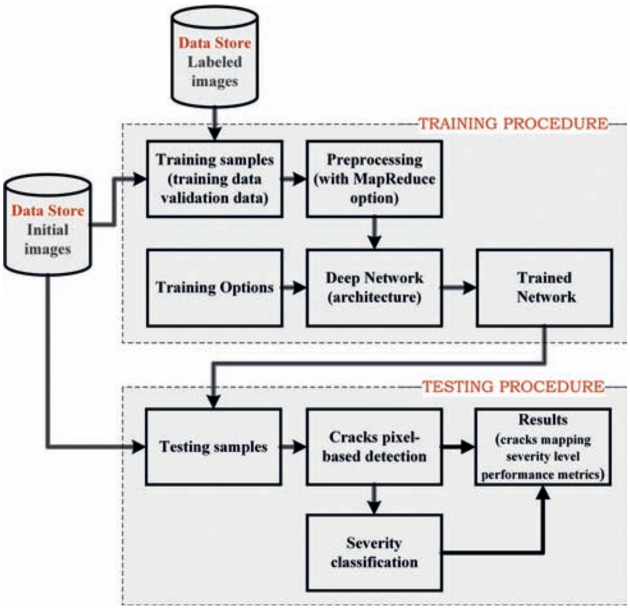

Figure 4. Main modules of the crack detection and classification algorithm

We refer to [11] for more details on preprocessing and ROI identification. The edge detection methodology discussed in [11] defines the architecture of CNN used in the solution of (4) (see Fig. 5).

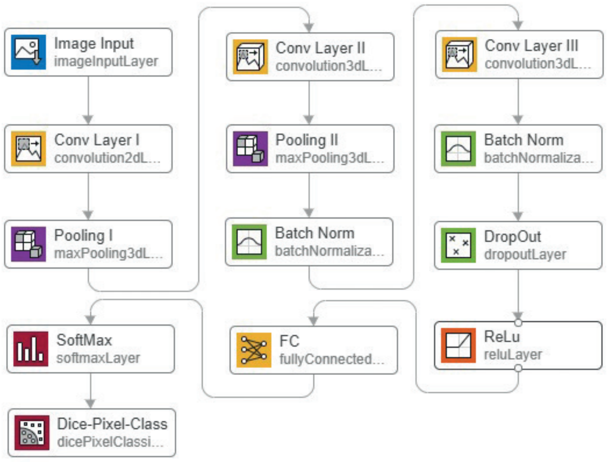

Figure 5. Sketch of overall architecture of "Deep Network" module.

To reduce the training time, the training procedure is implemented as a general MapReduce architecture. The main idea of this framework can be shortly described as follows. First training samples are divided on chunks. Each chunk is treated separately in parallel mode to perform a network training (data preprocessing, the weights initialization, forward propagation, backward propagation, the calculation of deviation, the calculation of offset, weights update such that to insure the convergence of the goal function (4)). As a result a "Key Value Store" is created. Next, these values are grouped by unique keys and reduced such that "Key Value Store" contains the parameters of the trained predictive model [19].

3.2. Evaluation metrics

The main idea of the crack detection algorithm is a binary classification of pixels as "cracked" or "non-cracked". Hence, to analyze the liaison between predicted and labeled ROIs, each target crack was marked by a minimum enclosing rectangle. The spatial coordinates of this last were used to indicate ROIs on the training sample. Therefore, accuracy of the classification can be measured by standard evaluation metrics such as

- precision

$$PPV = \frac{TP}{TP+FP}, \tag{6}$$

- recall sensitivity

$$TPR = \frac{TP}{TP+FN}, \tag{7}$$

- F1-score

$$F_1 = 2\frac{PPV \cdot TPR}{PPV+TPR}, \tag{8}$$

where TP and TN are the numbers of correctly classified "crack" and "non-crack" pixels as well as FP and FN are the number of misclassified pixels. These metrics can be used in a case of the severance-leveled classification. To study the global performance of this classification the mean-intersection-over-union is used. It can be estimated as

$$\overline{IoU} = \frac{1}{K}\sum_{k\in\{1,\ldots,K\}} \frac{TP_k}{TP_k+FP_k+FN_k}, \tag{10}$$

where K refers to the number of classes.

4. EXPERIMENT AND ANALYSIS

4.1. Dataset

The dataset consists of several concrete slab survey images with the same resolution. As it was mentioned before, the cracks areas are usually smaller than that of the total background. Hence, to avoid overloads of the training process we selected 4500 smaller blocks with a size 1024×1024 pixels. Next, on 300 patterns the cracks were manually labeled. Each labeled image was treated as the ground truth with two classes: "crack" and "no-crack" (see Fig. 6). The "crack" class was subdivided into four subclasses to indicate the severity level ("0" if $\overline{u} < 2mm$, "1" if $2mm \le \overline{u} < 4mm$, "2" if , "3" if $\overline{u} \ge 6mm$[1]). For

[1] This is just an example of classification. In practice, the norms have to be applied to define the severity classes [17, 18].

training-evaluation purposes the dataset was split on training, validation and test parts as 3:1:2.

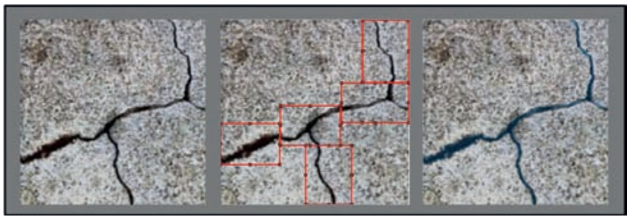

Figure 6. Example of image part selection and labeling

4.2. Implementation details

We used the personal computer with processor Intel (R) Core (TM) i7-470HQ CPU@2.50GHz RAM 16 Go and graphic card NVIDIA GeForce GTX 860M 1029MHz under 64-bit Windows 8.1 OS to explore the performance of the proposed methodology. The crack detection and classification algorithm was implemented in MatLab R2020b with DeepLearning, Parallel Computing and Computer Vision Toolboxes. MapReduce framework was executed on a parallel pool of four workers. The resolution parameter was automatically detected on the set of 100 images. This parameter was allied to find the average opening of detected cracks. The network was trained with the initial learning rate – "0.0001", the maximum number of epochs – "50", size of the mini-batch to use for each training iteration was "64", the validation frequency – "50". To insure the conversance of (4) we used the Adam optimization method setting $\varepsilon = 10^{-9}$, gradient decay factor as "0.9", squared decay factor as "0.999". Moreover, a random flip was applied to improve the robustness of the trained model.

4.3. Detection results

In the first stage of experiment we were interested only in binary classification task: the potential to find cracks. The performance of the proposed crack detection methodology (it is called as "*Method*" or "*MethodMR*" if MapReduce framework is applied) was compared with other semantic segmentation techniques based on the CNN architecture (U-Net [20] and CrackNet [15]). The experimental setup parameters as well as training, evaluation, and testing datasets were the same for each method. The methodology discussed in this paper was running twice: without MapReduce and with MapReduce framework. Table 3 contains the quantitative comparison of these methods using on the evaluation metrics (6) – (9) as well as training-evaluation time to finalize the predictive model. As it is possible to see, the proposed segmentation method supported by MapReduce framework achieves the highest performance. Results expose higher accuracy in binary classification and improvements in speedup and coincide with these were reported in [14, 18, 19].

Table 3. The performance comparison results on cracks detection using different architectures of CNN

CNN	PPV [%]	TPR [%]	F_1 [%]	$\overline{I_0U}$ [%]	$t_{tranining}$ [s]
U-Net	95.87	96.04	95.95	71.33	2784
CrackNet	96.18	97.09	96.63	72.54	2208
Method	97.99	97.43	97.71	74.15	2160
MethodMR	98.21	92.39	92.30	75.62	857

In the second stage of experiment, we have analyzed the severity levels detected by MethodMR. The severity classification results for one image are shown in Fig. 7. To evaluate the multiclass predictive model we use the receiver operating characteristic (ROC) curves (see Fig. 8) and estimated areas under the curves (AUC), namely:

$$AUC_{Class"0"} = 0.9159,\ AUC_{Class"1"} = 0.9488,$$
$$AUC_{Class"2"} = 0.9601,\ AUC_{Class"3"} = 0.9754.$$

As it is possible to see, *MethodMR* has better in-sample performance in classifying cracks with bigger openings.

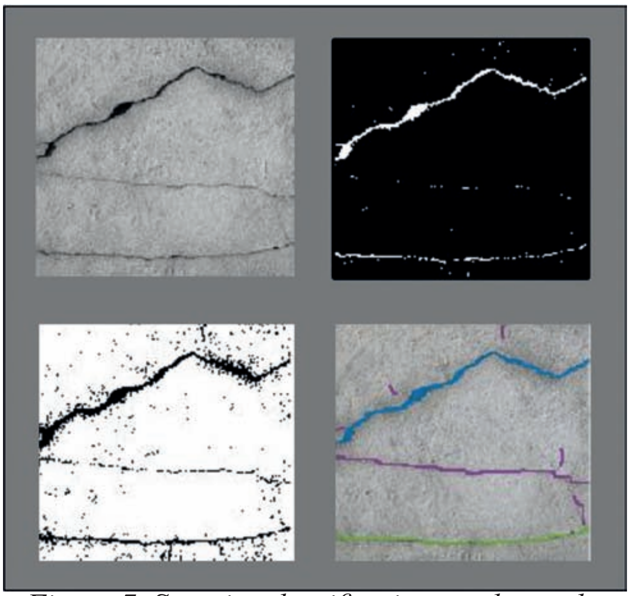

Figure 7. Severity classification marks on the test image ("purple" – class "1", "green" – class "2", "blue" – class "3")

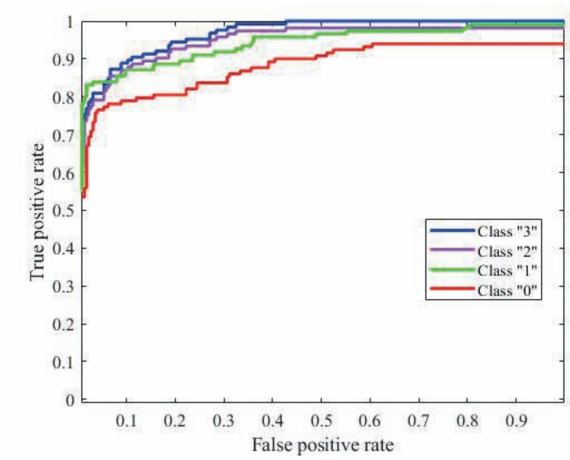

Figure 8. ROC curves for severity classification

5. CONCLUSIONS

The machine learning methods and especially convolutional neural networks have gained recognition in a wide array of applications of civil engineering permitting resolving the well-known problem of computer vision with better precision. Nonetheless, due to the enlargement of available information, the rise of computational complexity is observed. Big data severely impact training processes of CNN. The finalization of the CNN-based predictive model with desired accuracy suitable for the application has very high computational cost.

To overcome these obstacles, this study presented a novel semantic segmentation strategy for the automatic detection of cracks based on the distributed framework MapReduce applied to CNN training phase. The proposed method showed significant acceleration comparing to other segmentation networks. Moreover, results of cracks detection and classification reveal high accuracy. The proposed solution can be adapted to the specificity of the field of application to develop high-throughput damage detection systems implemented in portable devices using cloud technologies.

REFERENCES

1. **Papanicolaou C.G., Papantoniou I.C.** Optimum design of textile-reinforced concrete as integrated formwork in slabs // Editor(s): Thanasis Triantafillou, Textile Fibre Composites in Civil Engineering, Woodhead Publishing, 2016, pp. 245–274.
2. **Roetzel W., Luo X., Chen D.** Optimal design of heat exchanger networks // Editor(s): Wilfried Roetzel, Xing Luo, Dezhen Chen, Design and Operation of Heat Exchangers and their Networks, Academic Press, 2020, pp. 231–317.
3. **Behera B.K.** Modeling the structure of woven fabrics // Editor(s): K.L. Gandhi, [In] Woodhead Publishing Series in Textiles, Woven Textiles, Woodhead Publishing, 2012, pp. 229–263.
4. **Chen CJ.** An integrating genetic algorithm and modified Newton method for tracking control and vibration suppression // Artif Intell Rev, 2020, Vol. 53, pp. 3177–3199.
5. **Li L., Liu F.** Application of Particle Swarm Optimization Algorithm to Engineering Structures // [In] Group Search Optimization for Applications in Structural Design. Adaptation, Learning, and Optimization, vol 9. Springer, Berlin, Heidelberg, 2011.

6. **Filatova D.** Multi-agent simulation for self-healing mechanisms of damaged geotechnical structures // International Journal for Computational Civil and Structural Engineering, 2019, Vol. 15(4), pp. 48–57.
7. **Braun C.E., Chiwiacowsky L.D., Gómez A.T.** Variations of Ant Colony Optimization for the Solution of the Structural Damage Identification Problem // Procedia Computer Science, 2015, Vol. 51, pp. 875–884.
8. **Sonmez M.** Artificial Bee Colony algorithm for optimization of truss structures // Applied Soft Computing, 2011, Vol. 11 (2), pp. 2406–2418.
9. **Wang GG., Gandomi A.H., Alavi A.H. et al.** A comprehensive review of krill herd algorithm: variants, hybrids and applications // Artif Intell Rev, 2019, Vol. 51, pp. 119–148.
10. **Hakim S.J.S., Razak H.A., Ravanfar S.A.** Fault diagnosis on beam-like structures from modal parameters using artificial neural networks // Measurement, 2015, Vol. 76, pp. 45–61.
11. **Filatova D., El-Nouty Ch., Punko U.** High-throughput deep learning algorithm for diagnosis and defects classification of waterproofing membranes // International Journal for Computational Civil and Structural Engineering, 2020, Vol. 16(2), pp. 26–38.
12. **Avci O., Abdeljaber O., Kiranyaz S., Hussein M., Gabbouj M., Inman D.J.** A review of vibration-based damage detection in civil structures: From traditional methods to Machine Learning and Deep Learning applications, Mechanical Systems and Signal Processing, 2021, Vol. 147, pp. 107077
13. **Song Y., Huang Z., Shen Ch., Humphrey Shi, Lange D.A.** Deep learning-based automated image segmentation for concrete petrographic analysis // Cement and Concrete Research, 2020, Vol. 135, 106118.
14. **Zhang A., Wang K.C.P., Li B.X., Yang E.H., Dai X.X. et al.** Automated pixel-level pavement crack detection on 3D asphalt surfaces using a deep-learning network // Computer-Aided Civil and Infrastructure Engineering, 2017, Vol. 32 (10), pp. 805–819.
15. **Zhang A., Wang K.C.P., Fei Y., Liu Y., Tao S.Y.** Deep learning-based fully automated pavement crack detection on 3d asphalt surfaces with an improved CrackNet // Journal of Computing in Civil Engineering, 2018, Vol. 32 (50), 04018041.
16. **Huang Y., Li J., Fu J.** Review on Application of Artificial Intelligence in Civil Engineering // Computer Modeling in Engineering & Sciences, 2019, Vol. 121 (3), pp. 845–875.
17. **Oliveira H., Lobato Correia P.** CrackIT – an image processing toolbox for crack detection and characterization // 2014 IEEE International Conference on Image Processing (ICIP), Paris, 2014, pp. 798–802.
18. **Song W., JiaG., Jia D., Zhu H.** Automatic Pavement Crack Detection and Classification Using Multiscale Feature Attention Network // IEEE Access, 2019, Vol. 7, pp. 171001-171012.
19. **Zhao C., Dong M., Ota K., Wu J., Li J. and Li G.** MapReduce Enabling Content Analysis Architecture for Information-Centric Networks Using CNN // 2018 IEEE International Conference on Communications (ICC), Kansas City, MO, 2018, pp. 1–6.
20. **Ronneberger O., Fischer P., Brox T.** U-Net: Convolutional Networks for Biomedical Image Segmentation // [In]: Navab N., Hornegger J., Wells W., Frangi A. (eds) Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015. MICCAI 2015. Lecture Notes in Computer Science, 2015, pp. 234–241.

СПИСОК ЛИТЕРАТУРЫ

1. **Papanicolaou C.G., Papantoniou I.C.** Optimum design of textile-reinforced concrete as integrated formwork in slabs // Editor(s): Thanasis Triantafillou, Textile Fibre Composites in Civil Engineering, Woodhead Publishing, 2016, pp. 245–274.
2. **Roetzel W., Luo X., Chen D.** Optimal design of heat exchanger networks // Editor(s): Wilfried Roetzel, Xing Luo, Dezhen Chen,

Design and Operation of Heat Exchangers and their Networks, Academic Press, 2020, pp. 231–317.
3. **Behera B.K.** Modeling the structure of woven fabrics // Editor(s): K.L. Gandhi, [In] Woodhead Publishing Series in Textiles, Woven Textiles, Woodhead Publishing, 2012, pp. 229–263.
4. **Chen CJ.** An integrating genetic algorithm and modified Newton method for tracking control and vibration suppression // Artif Intell Rev, 2020, Vol. 53, pp. 3177–3199.
5. **Li L., Liu F.** Application of Particle Swarm Optimization Algorithm to Engineering Structures // [In] Group Search Optimization for Applications in Structural Design. Adaptation, Learning, and Optimization, vol 9. Springer, Berlin, Heidelberg, 2011.
6. **Filatova D.** Multi-agent simulation for self-healing mechanisms of damaged geotechnical structures // International Journal for Computational Civil and Structural Engineering, 2019, Vol. 15(4), pp. 48–57.
7. **Braun C.E., Chiwiacowsky L.D., Gómez A.T.** Variations of Ant Colony Optimization for the Solution of the Structural Damage Identification Problem // Procedia Computer Science, 2015, Vol. 51, pp. 875–884.
8. **Sonmez M.** Artificial Bee Colony algorithm for optimization of truss structures // Applied Soft Computing, 2011, Vol. 11 (2), pp. 2406–2418.
9. **Wang GG., Gandomi A.H., Alavi A.H. et al.** A comprehensive review of krill herd algorithm: variants, hybrids and applications // Artif Intell Rev, 2019, Vol. 51, pp. 119–148.
10. **Hakim S.J.S., Razak H.A., Ravanfar S.A.** Fault diagnosis on beam-like structures from modal parameters using artificial neural networks // Measurement, 2015, Vol. 76, pp. 45–61.
11. **Filatova D., El-Nouty Ch., Punko U.** High-throughput deep learning algorithm for diagnosis and defects classification of waterproofing membranes // International Journal for Computational Civil and Structural Engineering, 2020, Vol. 16(2), pp. 26–38.
12. **Avci O., Abdeljaber O., Kiranyaz S., Hussein M., Gabbouj M., Inman D.J.** A review of vibration-based damage detection in civil structures: From traditional methods to Machine Learning and Deep Learning applications, Mechanical Systems and Signal Processing, 2021, Vol. 147, pp. 107077
13. **Song Y., Huang Z., Shen Ch., Humphrey Shi, Lange D.A.** Deep learning-based automated image segmentation for concrete petrographic analysis // Cement and Concrete Research, 2020, Vol. 135, 106118.
14. **Zhang A., Wang K.C.P., Li B.X., Yang E.H., Dai X.X. et al.** Automated pixel-level pavement crack detection on 3D asphalt surfaces using a deep-learning network // Computer-Aided Civil and Infrastructure Engineering, 2017, Vol. 32 (10), pp. 805–819.
15. **Zhang A., Wang K.C.P., Fei Y., Liu Y., Tao S.Y.** Deep learning-based fully automated pavement crack detection on 3d asphalt surfaces with an improved CrackNet // Journal of Computing in Civil Engineering, 2018, Vol. 32 (50), 04018041.
16. **Huang Y., Li J., Fu J.** Review on Application of Artificial Intelligence in Civil Engineering // Computer Modeling in Engineering & Sciences, 2019, Vol. 121 (3), pp. 845–875.
17. **Oliveira H., Lobato Correia P.** CrackIT – an image processing toolbox for crack detection and characterization // 2014 IEEE International Conference on Image Processing (ICIP), Paris, 2014, pp. 798–802.
18. **Song W., JiaG., Jia D., Zhu H.** Automatic Pavement Crack Detection and Classification Using Multiscale Feature Attention Network // IEEE Access, 2019, Vol. 7, pp. 171001–171012.
19. **Zhao C., Dong M., Ota K., Wu J., Li J. and Li G.** MapReduce Enabling Content Analysis Architecture for Information-Centric Networks Using CNN // 2018 IEEE International Conference on Communications (ICC), Kansas City, MO, 2018, pp. 1–6.
20. **Ronneberger O., Fischer P., Brox T.** U-Net: Convolutional Networks for Biomedical

Image Segmentation // [In]: Navab N., Hornegger J., Wells W., Frangi A. (eds) Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015. MICCAI 2015. Lecture Notes in Computer Science, 2015, pp. 234–241.

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DETERMINING THE LENGMUR COEFFICIENT OF THE FILTRATION PROBLEM

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Abstract: Filtration of suspension in a porous medium is actual in the construction of tunnels and underground structures. A model of deep bed filtration with size-exclusion mechanism of particle capture is considered. The inverse filtration problem – finding the Langmuir coefficient from a given concentration of suspended particles at the porous medium outlet is solved using the asymptotic solution near the concentrations front. The Langmuir coefficient constants are obtained by the least squares method from the condition of best approximation of the asymptotics to exact solution. It is shown that the calculated parameters are close to the coefficients of the model, and the asymptotics well approximates the exact solution.

Keywords: deep bed filtration, porous medium, mathematical model, asymptotics, inverse problem

О НАХОЖДЕНИИ КОЭФФИЦИЕНТА ЛЕНГМЮРА ЗАДАЧИ ФИЛЬТРАЦИИ

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Аннотация: Задачи фильтрации суспензии в пористой среде актуальны при строительства туннелей и подземных сооружений. Рассматривается модель долговременной глубинной фильтрации с размерным механизмом задержания частиц. На основе асимптотики вблизи фронта концентраций взвешенных и осажденных частиц решается обратная задача фильтрации – нахождение коэффициента Ленгмюра по заданной концентрации взвешенных частиц на выходе пористой среды. Константы коэффициентов Ленгмюра находятся методом наименьших квадратов из условия наилучшего приближения асимптотики к точному решению. Показано, что вычисленные параметры близки к коэффициентам модели, а найденная асимптотика хорошо приближает точное решение.

Ключевые слова: долговременная глубинная фильтрация, пористая среда, математическая модель, асимптотика, обратная задача

1. INTRODUCTION

Transport and retention of solid particles in a porous medium occur in various natural phenomena and in industrial technologies. During the construction of tunnels and underground structures to create waterproof partitions, liquid concrete is pumped into the rock. The solution spreads through the pores and when solidified, forms a waterproof wall [1].

The transport of suspensions and colloids in porous media is accompanied by the retention of particles, which get stuck in the pores and form a deposit. The reasons for particle retention in porous media are straining, attachment, bridging, diffusion into dead-end pores, etc. [2, 3]. The intensity of various particle capture mechanisms depends on the physical and chemical properties of the particles, carrier fluid, and porous rock. If the particle and pore size distributions overlap, the predominant cause of retention is the blocking of large particles in small pores. This capture mechanism is called size-exclusion [4]. It is assumed that the retained particles cannot be knocked out of the pore throat by the fluid flow or suspended particles and always remain stationary.

The mathematical model of filtration includes the equation of mass balance of suspended and retained particles and the kinetic equation of deposit growth [5]. At low concentrations of suspended particles, the deposit growth rate is proportional to the first degree of suspended particles concentration. The proportionality coefficient depends on the concentration of the retained particles and is called the filtration function.

Mathematical models often have analytical solutions. For some problems, it is possible to obtain a global or local exact solution; in other cases, the asymptotics is constructed [6-9]. Analytical solutions allow to compare the mathematical model with the experiment and determine the parameters of the model from experimental data. The inverse filtration problem is to obtain the filtration function by the known concentration of suspended particles at the outlet of the porous medium, which can be measured in the laboratory.

For a simple filtration model that does not take into account the change in porosity during deposit growth, the inverse problem was solved in [10–12] by the method of successive approximations. The solution is based on Riemann relation between the concentrations of suspended and retained particles inside a porous medium at an arbitrary time moment with the concentrations at the porous medium inlet. However, this method is not applicable for complex filtration models in which several equation coefficients are functions of the concentrations of suspended and retained particles.

In this article a new asymptotic method for solving the inverse filtering problem is proposed. Asymptotic formulas defining a solution to the filtration problem depend on the model parameters in explicit form. Equating the asymptotics to the given solution at the output of the porous medium, all the parameters of the model are determined.

In the simplest filtration model, the filtration function is a linear non-negative decreasing function of the retained particles concentration. Such a filtration function, called the Langmuir coefficient, is often used in mathematical models [13, 14]. Below, the asymptotic method for solving the filtration problem is used to obtain the parameters λ_0, λ_1 of the Langmuir coefficient.

2. MATHEMATICAL MODEL

The one-dimensional model of suspension and colloid filtration in a porous medium is defined by a system of partial differential equations of the first order with unknown concentrations of suspended $C(x,t)$ and retained $S(x,t)$ particles

$$\frac{\partial(C+S)}{\partial t}+\frac{\partial C}{\partial x}=0\,; \qquad (1)$$

$$\frac{\partial S}{\partial t}=\Lambda(S)C\,. \qquad (2)$$

Here the filtration function $\Lambda(S)$ is a continuous positive decreasing function.

The dimensionless system of equations (1), (2) is considered in the domain

$$\Omega=\{0\le x\le 1,\ t\ge 0\}.$$

The boundary conditions for system (1), (2) are set at the inlet of the porous medium $x = 0$ and at the initial time $t = 0$:

$$C(x,t)\big|_{x=0}=1\,; \qquad (3)$$

$$C(x,t)\big|_{t=0}=0\,; \qquad (4)$$

$$S(x,t)\big|_{t=0}=0\,. \qquad (5)$$

At the initial moment $t = 0$, the porous medium does not contain any suspended and retained particles. The concentrations front of suspended and retained particles $t = x$ moves from the porous medium inlet $x = 0$ to the outlet $x = 1$ at a speed $v = 1$. Before the front in the domain $\Omega_0 = \{0 \le x \le 1,\ t < x\}$, the porous medium is empty and the problem has a zero solution $C(x,t) = 0$; $S(x,t) = 0$. Behind the front in the domain

$$\Omega_S = \{0 \le x \le 1,\ t > x\}$$

a suspension and retained particles are present; the solution is positive $C(x,t) > 0$; $S(x,t) > 0$. At the concentration front, the solution $S(x,t)$ is continuous, the solution $C(x,t)$ has a gap.

A filtration function $\Lambda(S)$ that has a positive root is called a blocking filtration function. The most commonly used filtration function is the Langmuir coefficient [15]

$$\Lambda(S) = \lambda_0 - \lambda_1 S,\ \lambda_0 > 0,\ \lambda_1 > 0. \tag{6}$$

In a domain Ω_S the problem (1)–(5) with Langmuir coefficient (6) has exact solution in explicit form [13]

$$C_{ex} = \frac{e^{\lambda_1(t-x)}}{e^{\lambda_1(t-x)} + e^{\lambda_0 x} - 1} \tag{7}$$

In the vicinity of the concentration front $t = x$, the second-order asymptotic solution to problem (1)–(6) has the form [16]

$$\begin{aligned} C_{as} &= e^{-\lambda_0 x} + \lambda_1 (e^{-\lambda_0 x} - e^{-2\lambda_0 x})(t-x) \\ &+ \lambda_1^2 \left(2e^{-3\lambda_0 x} - 3e^{-2\lambda_0 x} + e^{-\lambda_0 x}\right)(t-x)^2/2. \end{aligned} \tag{8}$$

3. INVERSE PROBLEM

Suspended particles appear at the porous medium outlet at the moment $t = 1$ because the length of the porous medium sample $l = 1$ and the concentration front moves with speed $v = 1$. The inverse problem is to obtain the filtration function $\Lambda(S)$ by the known suspended particles concentration $C(1,t)$ at the outlet of the porous medium.

Denote $\tau = t - 1$.

Exact and asymptotic solutions of the suspended particles concentration at the outlet of the porous medium are obtained by substituting $x = 1$ in formulas (7), (8)

$$C_{ex}(1,\tau) = \frac{e^{\lambda_1 \tau}}{e^{\lambda_1 \tau} + e^{\lambda_0 x} - 1} \tag{9}$$

$$\begin{aligned} C_{as}(1,\tau) &= e^{-\lambda_0} + \lambda_1 (e^{-\lambda_0} - e^{-2\lambda_0})\tau \\ &+ \lambda_1^2 \left(2e^{-3\lambda_0} - 3e^{-2\lambda_0} + e^{-\lambda_0}\right)\tau^2/2 \end{aligned} \tag{10}$$

In the laboratory of the Australian School of Petroleum & Energy Resources of the University of Adelaide, Australia, experiments were carried out to filter the suspension in a porous medium [17, 18]. Chemical composition and size of the particles were selected so that size-exclusion was the main particle capture mechanism. According to the experiments, the parameters Λ_0, Λ_1 of the Langmuir coefficients $\Lambda(S) = \Lambda_0 - \Lambda_1 S$ were obtained for filtration of monodisperse suspensions with solid particles of three sizes (see Table 1).

Table 1. Experimental Langmuir coefficients

Particle radius r_n, μ	Λ_0	Λ_1
$r_1 = 1.568$	0,11	0,01351
$r_2 = 2.179$	0,59	0,005956
$r_1 = 3.168$	1,551	0,003457

The unknown constants λ_0, λ_1 in the Langmuir coefficient (6) are determined by comparing the exact solution $C_{ex}(1,\tau)$ at the porous medium outlet of problem (1)–(5) calculated for the Langmuir coefficients given in Table 1 with the asymptotics (8). The constant λ_0 is determined by the suspended particles concentration at the time of the appearance of the suspension at the outlet of the porous medium (so called break-through concentration)

$$\tau = 0: \quad C_{as}(1,0) = e^{-\lambda_0} = C_{ex}(1,0)$$
$$\Rightarrow \ \lambda_0 = -\ln C_{ex}(1,0).$$

The constant λ_1 is obtained from the condition of the best approximation of the asymptotics to the exact solution by the least squares method on the interval $\tau \in [0; 10]$.

4. NUMERICAL CALCULATION

To find the constant λ_1, the integral of the square of the difference between the exact and asymptotic solutions with the variable parameter λ_1 over the interval $\tau \in [0;\ 10]$ in the explicit form was calculated. The derivative of the integral with respect to the variable λ_1 is a third-order polynomial. The polynomial has 3 real roots for all three types of particles. Real polynomial root closest to the experimental constant Λ_1 is the desired approximation of the constant λ_1.
The results of calculating the constants λ_0, λ_1 are presented in Table 2.

Table 2. Experimental & calculated constants

r_n, μ	Λ_0	λ_0	Λ_1	λ_1
$r_1 = 1.568$	0,11	0,11	0,01351	0,01352
$r_2 = 2.179$	0,51	0,51	0,005956	0,005955
$r_3 = 3.168$	1,551	1,551	0,003467	0,003467

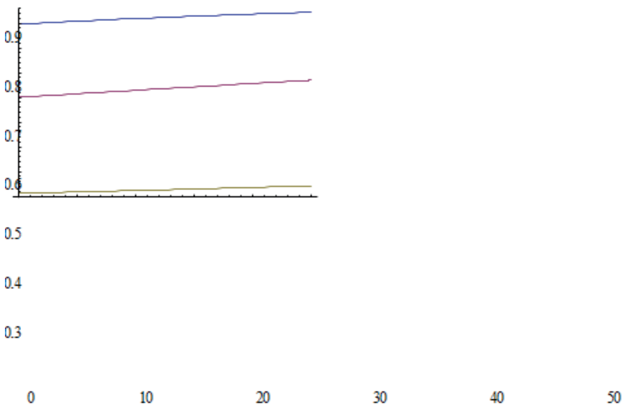

Figure 1. Suspended particles concentrations of 3 particle sizes at the outlet x = 1

According to Table 2, the relative error in finding the constants is less then 0.01%; the error decreases with increasing particle radius.
Figure 1 shows the suspended particles concentrations of three particle sizes at the porous medium outlet: 1 – blue, 2 – red, 3 – brown. At $t \leq 50$ the graphs of exact solution and asymptotics coincide for all three types of particles.
The graph sections with high resolution are shown in Figure 2 (the exact solution is blue, the asymptotics is red).
According to Figure 2 a), b), c) at time $t \leq 10$, the relative error of the asymptotics regarding exact solution is less than 0.001% for all types of particles.

5. CONCLUSION

An asymptotic method for solving the inverse filtering problem is studied. For example, the constants of the Langmuir coefficients are found. The parameters of the mathematical model are determined by comparing the exact solution with the asymptotics at the porous medium output.
It is shown that the least squares method is an effective way to obtain the model parameters. The coefficients of the filtration function are determined with an accuracy of 0.01%; when $t \leq 10$ the asymptotics differs from the exact solution less than 0.001%.
In the laboratory, the parameters of the mathematical model should be determined by measuring the concentration of suspended particles at the porous medium outlet [19]. In this case, the accuracy of finding the coefficients may deteriorate due to errors in laboratory measurements and deviations of the mathematical model from experimental conditions.

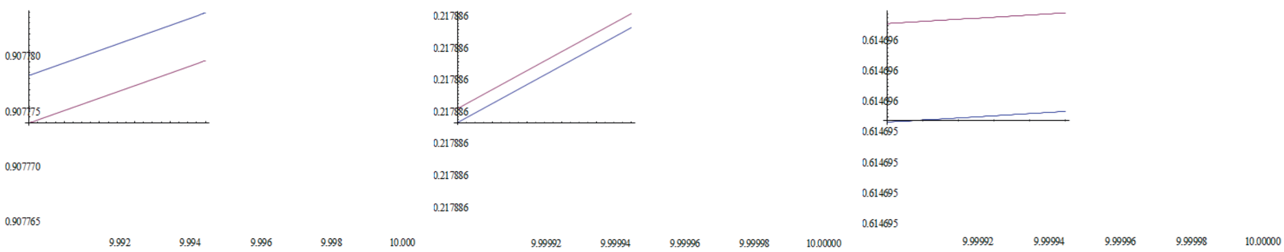

Figure. 2. Graph sections of the suspended particles concentrations at the porous medium outlet

The next step in solving the inverse filtration problem is to obtain an unknown nonlinear filtration function that depends on 3 or more constants. In this case, problem (1)–(5) does not have an exact solution in explicit form. To solve the inverse problem, a numerical solution by the finite difference method is required [20, 21].

REFERENCES

1. **Strømsvik H.** The significance of hydraulic jacking for grout consumption during high pressure pre-grouting in Norwegian tunnelling. // Tunnelling and Underground Space Technology, 2019, vol. 90, pp. 357–368.
2. **Civan F.** Reservoir formation damage, third ed. Gulf Professional Publishing, Burlington, MA, USA, 2014.
3. **Mays D.C., Hunt J.R.** Hydrodynamic and chemical factors in clogging by montmorillonite in porous media. // Environmental Science and Technology, 2007, vol. 41, pp. 5666–5671.
4. **Santos A., Bedrikovetsky P., Fontoura S.** Analytical micro model for size exclusion: Pore blocking and permeability reduction. // Journal of Membrane Science, 2008, vol. 308, pp 115–127.
5. **Herzig J.P., Leclerc D.M., Legoff P.** Flow of suspensions through porous media - application to deep filtration. // Industrial and Engineering Chemistry, 1970, vol. 62(5), pp. 8–35.
6. **Kuzmina L.I., Osipov Yu.V., Vetoshkin N.V.** Calculation of long-term filtration in a porous medium. // International Journal for Computational Civil and Structural Engineering, 2018, vol. 14(1), pp. 92–101.
7. **Kuzmina L.I., Osipov Y.V., Zheglova Y.G**. Modelling uniform asymptotics of the filtration problem in a porous medium. // IOP Conference Series: Materials Science and Engineering, 2018, vol. 456, 012051.
8. **Kuzmina L.I., Osipov Yu.V., Zheglova Yu.G**. Global asymptotics of the filtration problem in a porous medium. // International Journal for Computational Civil and Structural Engineering, 2019, vol. 15(2), pp. 77–85.
9. **Kuzmina L.I., Nazaikinskii V.E., Osipov Yu.V.** On a deep bed filtration problem with finite blocking time. // Russian Journal of Mathematical Physics, 2019, vol. 26(1), pp. 130–134.
10. **Alvarez A.C., Bedrikovetsky P.G., Hime G., Marchesin A.O., Marchesin D., Rodrigues J.R.** A fast inverse solver for the filtration function for flow of water with particles in porous media. // Inverse Problems, 2006, vol. 22, pp. 69–88.
11. **Alvarez A.C., Hime G., Marchesin D., Bedrikovetsky P.G.** The inverse problem of determining the filtration function and permeability reduction in flow of water with particles in porous media. // Transport in Porous Media, 2007, vol. 70(1), pp. 43–62.
12. **Alvarez A.C., Hime G., Silva J.D., Marchesin D.** Analytic regularization of an inverse filtration problem in porous media. // Inverse Problems, 2013, vol. 29, 025006.
13. **Vyazmina E.A., Bedrikovetskii P.G., Polyanin A.D.** New classes of exact solutions to nonlinear sets of equations in the theory of filtration and convective mass transfer. // Theoretical Foundations of Chemical Engineering, 2007, vol. 41(5), pp. 556–564.
14. **Malgaresi G., Collins B., Alvaro P., Bedrikovetsky P.** Explaining non-monotonic retention profiles during flow of size-distributed colloids. // Chemical Engineering Journal, 2019, vol. 375, 121984.
15. **Altoe J.E., Bedrikovetsky P., Siqueira A.G., de Souza A.L.S., Shecaira F.S.** Correction of basic equations for deep bed filtration with dispersion. // Journal of Petroleum Science and Engineering, 2006, vol. 51, pp. 68– 84.
16. **Osipov Yu., Kotov N.** Asymptotic model of size-exclusion grouting. // IOP Conference Series: Materials Science and Engineering, 2018, vol. 365, 042006.
17. **Oliveira P., Vaz A., Siqueira F., Yang Y., You Z.** Slow migration of mobilised fines during flow in reservoir rocks: Laboratory

study. // Journal of Petroleum Science and Engineering, 2014, vol. 122, pp. 534–541.
18. **Aji K., You Z., Badalyan A.** Transport and straining of suspensions in porous media: experimental and theoretical study. // Thermal Science, 2012, vol. 16(5), pp. 1344–1348.
19. **Badalyan A., You Z., Aji K., Bedrikovetsky P., Carageorgos T., Zeinijahromi A.** Size exclusion deep bed filtration: Experimental and modelling uncertainties. // Review of scientific instruments, 2014, vol. 85(1), 015111.
20. **Galaguz Y.P.** Realization of the TVD-scheme for a numerical solution of the filtration problem. // International Journal for Computational Civil and Structural Engineering, 2017, vol. 13(2), pp. 93–102.
21. **Galaguz Y.P., Safina G.L.** Modeling of fine migration in a porous medium. // MATEC Web of Conferences, 2016, vol. 86, 03003.

СПИСОК ЛИТЕРАТУРЫ

1. **Strømsvik H.** The significance of hydraulic jacking for grout consumption during high pressure pre-grouting in Norwegian tunnelling. // Tunnelling and Underground Space Technology, 2019, vol. 90, pp. 357–368.
2. **Civan F.** Reservoir formation damage, third ed. Gulf Professional Publishing, Burlington, MA, USA, 2014.
3. **Mays D.C., Hunt J.R.** Hydrodynamic and chemical factors in clogging by montmorillonite in porous media. // Environmental Science and Technology, 2007, vol. 41, pp. 5666–5671.
4. **Santos A., Bedrikovetsky P., Fontoura S.** Analytical micro model for size exclusion: Pore blocking and permeability reduction. // Journal of Membrane Science, 2008, vol. 308, pp 115–127.
5. **Herzig J.P., Leclerc D.M., Legoff P.** Flow of suspensions through porous media - application to deep filtration. // Industrial and Engineering Chemistry, 1970, vol. 62(5), pp. 8–35.
6. **Kuzmina L.I., Osipov Yu.V., Vetoshkin N.V.** Calculation of long-term filtration in a porous medium. // International Journal for Computational Civil and Structural Engineering, 2018, vol. 14(1), pp. 92–101.
7. **Kuzmina L.I., Osipov Y.V., Zheglova Y.G**. Modelling uniform asymptotics of the filtration problem in a porous medium. // IOP Conference Series: Materials Science and Engineering, 2018, vol. 456, 012051.
8. **Kuzmina L.I., Osipov Yu.V., Zheglova Yu.G**. Global asymptotics of the filtration problem in a porous medium. // International Journal for Computational Civil and Structural Engineering, 2019, vol. 15(2), pp. 77–85.
9. **Kuzmina L.I., Nazaikinskii V.E., Osipov Yu.V.** On a deep bed filtration problem with finite blocking time. // Russian Journal of Mathematical Physics, 2019, vol. 26(1), pp. 130–134.
10. **Alvarez A.C., Bedrikovetsky P.G., Hime G., Marchesin A.O., Marchesin D., Rodrigues J.R.** A fast inverse solver for the filtration function for flow of water with particles in porous media. // Inverse Problems, 2006, vol. 22, pp. 69–88.
11. **Alvarez A.C., Hime G., Marchesin D., Bedrikovetsky P.G.** The inverse problem of determining the filtration function and permeability reduction in flow of water with particles in porous media. // Transport in Porous Media, 2007, vol. 70(1), pp. 43–62.
12. **Alvarez A.C., Hime G., Silva J.D., Marchesin D.** Analytic regularization of an inverse filtration problem in porous media. // Inverse Problems, 2013, vol. 29, 025006.
13. **Vyazmina E.A., Bedrikovetskii P.G., Polyanin A.D.** New classes of exact solutions to nonlinear sets of equations in the theory of filtration and convective mass transfer. // Theoretical Foundations of Chemical Engineering, 2007, vol. 41(5), pp. 556–564.
14. **Malgaresi G., Collins B., Alvaro P., Bedrikovetsky P.** Explaining non-monotonic retention profiles during flow of size-distributed colloids. // Chemical Engineering Journal, 2019, vol. 375, 121984.

15. **Altoe J.E., Bedrikovetsky P., Siqueira A.G., de Souza A.L.S., Shecaira F.S.** Correction of basic equations for deep bed filtration with dispersion. // Journal of Petroleum Science and Engineering, 2006, vol. 51, pp. 68– 84.
16. **Osipov Yu., Kotov N.** Asymptotic model of size-exclusion grouting. // IOP Conference Series: Materials Science and Engineering, 2018, vol. 365, 042006.
17. **Oliveira P., Vaz A., Siqueira F., Yang Y., You Z.** Slow migration of mobilised fines during flow in reservoir rocks: Laboratory study. // Journal of Petroleum Science and Engineering, 2014, vol. 122, pp. 534–541.
18. **Aji K., You Z., Badalyan A.** Transport and straining of suspensions in porous media: experimental and theoretical study. // Thermal Science, 2012, vol. 16(5), pp. 1344–1348.
19. **Badalyan A., You Z., Aji K., Bedrikovetsky P., Carageorgos T., Zeinijahromi A.** Size exclusion deep bed filtration: Experimental and modelling uncertainties. // Review of scientific instruments, 2014, vol. 85(1), 015111.
20. **Galaguz Y.P.** Realization of the TVD-scheme for a numerical solution of the filtration problem. // International Journal for Computational Civil and Structural Engineering, 2017, vol. 13(2), pp. 93–102.
21. **Galaguz Y.P., Safina G.L.** Modeling of fine migration in a porous medium. // MATEC Web of Conferences, 2016, vol. 86, 03003.

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JUSTIFICATION OF STRENGTHENING A SLIDING BRIDGE SUPPORT (ON THE EXAMPLE OF THE BRIDGE THROUGH THE R. IZHORA ON THE HIGH-SPEED ROAD SAINT PETERSBURG – MOSCOW)

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Abstract: The article describes the experience of strengthening the foundations of the bridge support laying on a landslide slope. The bridge under consideration crosses the river Izhora in the Leningrad region. Numerical modeling of the process of development of support deformations is carried out. Analysis of the calculations showed that the development of the landslide process occurred as a result of waterlogging of the soil massif and soaking of soils at the base of support No. 10. Structural strengthening of the support in the form of buttresses was developed and numerically substantiated to eliminate deformation of the bridge support.

Keywords: deformations of bridge support, landslide slope, numerical modeling, strengthening with buttress

ОБОСНОВАНИЕ УСИЛЕНИЯ СПОЛЗАЮЩЕЙ МОСТОВОЙ ОПОРЫ (НА ПРИМЕРЕ МОСТА ЧЕРЕЗ Р. ИЖОРУ НА СКОРОСТНОЙ АВТОМОБИЛЬНОЙ ДОРОГЕ САНКТ-ПЕТЕРБУРГ – МОСКВА)

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Аннотация: В статье приведен опыт усиления фундаментов опоры моста в Ленинградской области через р. Ижора на оползневом склоне. Выполнено численное моделирование процесса развития деформаций опоры. Анализ расчетов показал, что развитие оползневого процесса произошло в результате переувлажнения грунтового массива и замачивания грунтов в основании опоры №10. Было разработано и численным методом обосновано конструктивное усиление опоры в виде контрфорсов для исключения деформирование опоры моста.

Ключевые слова: деформации опоры моста, оползневой склон, численное моделирование, усиление в виде контрфорсов

INTRODUCTION

During the period from November 2019 to February 2020 a geotechnical monitoring of the section of the Moscow – St. Petersburg high-speed highway in the area of the bridge over the river. Izhora (PK 6334) had been conducted. The geotechnical monitoring shown uneven deformations on support No 10L. The average rate of horizontal deformations of support No. 10L, according to geodetic observations, was up to 1.0 mm per day. As a result, it was necessary to develop recommendations for stabilizing the settlement to the axis of the track were 93 mm along the point. Figure 3 shows the layout of the marks and the measured displacement values.

The main deformations were noted in the inclinometric well No. 5, installed in the immediate

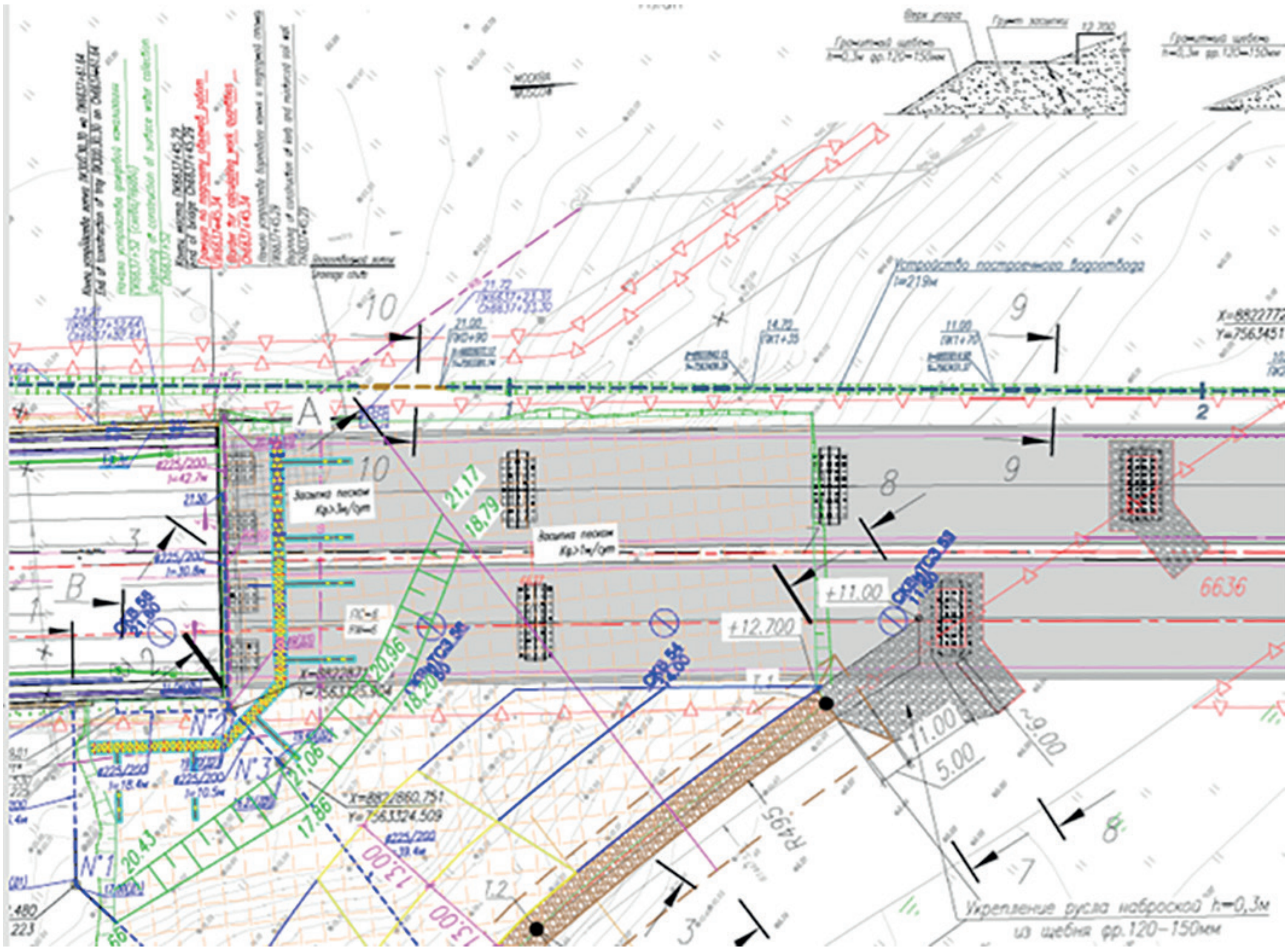

Figure 1. Location plan of the object of geotechnical analysis – support No. 10L

of the specified support, taking into account the projected structures of its strengthening.

The site is located on the left high bank of the river. Izhora. The relief of the site is characterized by the presence of a steep slope to the river. Izhora, located 15.0 m south of the site of additional surveys. The bridge supports are located on the not reinforced slope.

According to the monitoring results from 03.02.2020, the maximum horizontal displacements of the support parallel to the axis of the track were 148 mm, the horizontal deviations perpendicular

Figure 2. Actual situation at support No. 10L

vicinity of the support No. 10L and located in the upper soil layer to a depth of 3.5 m, while the maximum displacements at the surface were 60 mm along the X-axis , along the Y-axis – 27 mm.

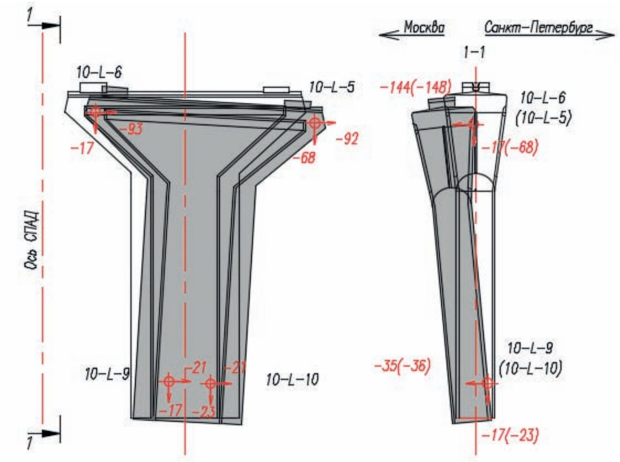

Figure 3. Layout of deformation marks and measured values of displacement on support No. 10L

1. ENGINEERING-GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS OF THE SITE

Geomorphologically, the construction site is located within the Pre-Glint Lowland.

In the geotechnical survey conducted by Morion LLC (2014) within the drilling depth to a depth of 20 m throughout the embankment and bridge construction site, 23 geotechnical elements (GE) were identified. CJSC "Len-TISIZ" performed additional, according to the results of which on the investigated site in the immediate vicinity of of the deformable retaining wall along the drilling depth of 15.0 m, 4 GE were allocated. Figure 4 shows the plan for additional working.

Additional engineering-geological surveys, in general, confirmed the previously noted bedding of soils. On the basis of the additional studies performed, in accordance with the requirements of GOST 20522-2012 and GOST 25100-2011, 4 GE were allocated in the study area. In the course of the additional surveys carried out at the site, the following engineering and geological elements were identified: GE 1 – bulk soils; GE 10b – semi-solid dislocated clays; GE 10 – hard clays deployed; GE 11 – hard clays.

The geological structure of the investigated area to a depth of 15.00 m is represented by modern technogenic (t IV) formations and Lower Cambrian deposits (Є1).

In the engineering-geological bedding of soils in the study area, soils of the Quaternary system – Q Modern deposits – Q IV, which lie from the surface and are represented by Technogenic formations – t IV take part.

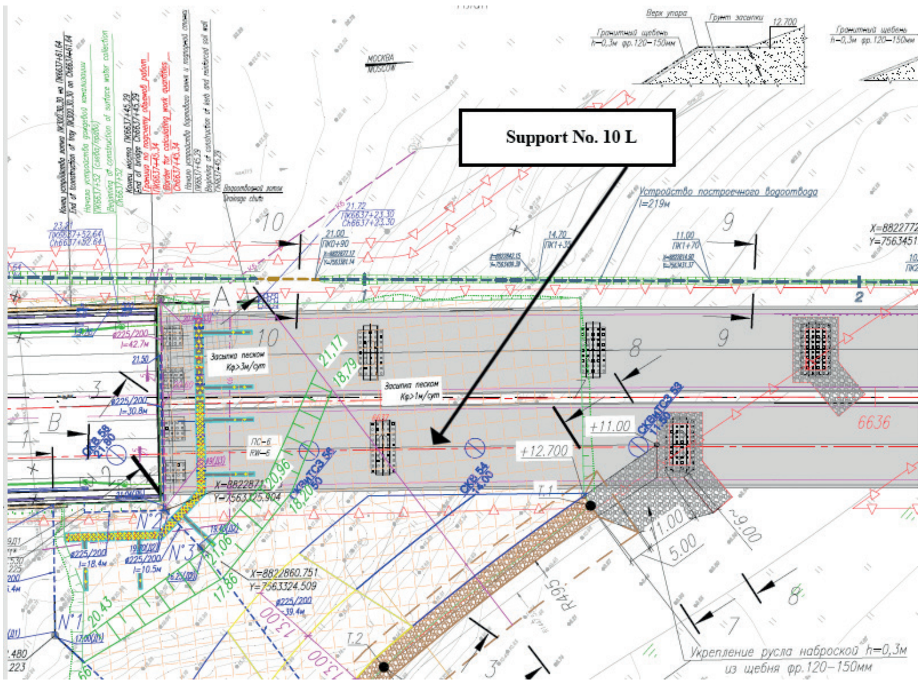

Figure 4. Location of additional geological workings on the plan (June 2019)

Modern technogenic formations tIV are represented by bulk non-caked soils and are distributed throughout the study area. They placed from the surface at a depth of 0.00 m (the absolute elevation of the roof is from 21.28 to 21.68 m), the thickness is 2.30–5.50 m.

Deposits of the Lower Cambrian Є1 are represented by semi-hard and hard clays, and hard clays. They lie under technogenic formations at a depth of 2.30–5.50 m (absolute roof elevation from 16.18 to 18.98 m), the exposed thickness is 9.50–12.70 m. Figure 5 shows the nature of bedding of soils.

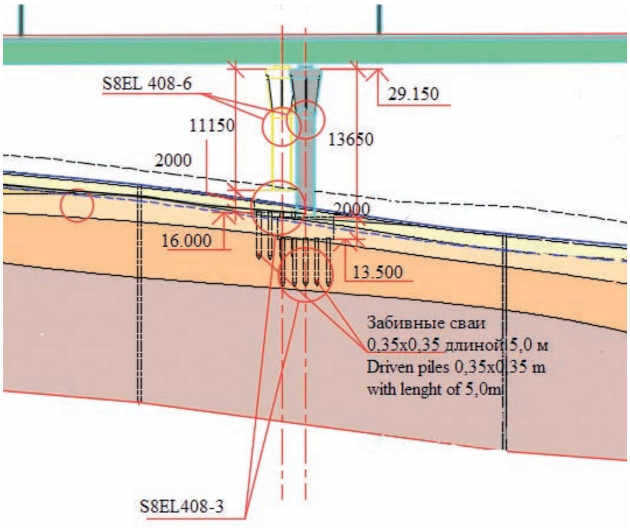

Figure 5. The nature of lying and relative position of the IGE at support 10 (based on materials from CJSC LenTIZ, 2019)

The results of additional studies carried out by LenTSIZ CJSC showed that non-caking loose soils (GE 1) lie on the surface, which in well No. 1 in depth from the day surface (0.00 m) to 0.9 m are represented by sands of different size mixed with gravel, pebbles, crushed stone of igneous and sedimentary rocks up to 15%; below, from a depth of 0.9 to 2.3 m – plastic sandy loam, mixed with large sand, with crushed stone of igneous and sedimentary rocks, with construction waste up to 20%. The fill-up soils at the time of the research were in a wet state.

In well No. 2, the fill soils have the following composition in terms of drilling depth: from the day surface to a depth of 1.3 m, they are represented by plastic sandy loams mixed with coarse sand, with crushed stone of igneous and sedimentary rocks, with construction waste up to 20%; in the depth range from 1.3 to 5.5 m, the fill soils include sands of various sizes, mixed with gravel, pebbles up to 10%, in the bottom of the fill soils there is a soil-vegetation layer. The soils are wet, saturated with water from a depth of 1.8 m. The filling period is less than 5 years.

Directly under the fill soils there are soils represented by the deposits of the Cambrian system of the Lower Section – Є1 in the form of GE10b, GE10 and GE 11.

GE 10b – Light dusty semi-solid clays, greenish-gray, with interlayers of solid and dusty, moist sands, with rare sandstone gruss. They lie under the fill soils at a depth of 2.30–5.50 m (absolute roof elevation from 16.18 to 18.98 m), the thickness reaches 1.00–1.20 m.

GE 10 – Light silty hard clays, dislocated, grayish-blue, with interlayers of silty, wet sands, with fragments of low-strength sandstones. They lie under semi-solid clays, deployed at a depth of 3.50–6.50 m (absolute elevation of the roof from 15.18 to 17.78 m), the thickness reaches 4.50–5.00 m.

GE 11 – Light silty hard clays, layered, grayish-blue, with interlayers of silty, wet sands and low-strength and medium-strength sandstones. They lie under the dislocation zone at a depth of 8.50 - 11.00 m (absolute elevation of the roof from 10.68 to 12.78 m), the exposed thickness reaches 4.00-6.50 m.

Based on the materials of additional surveys (CJSC LenTISIZ), the following soil filtration coefficients were adopted: for bulk soils tIV (GE 1) – 10.00 m / day; for the subsequent layers of soil located lower in depth, represented by GE 10b, GE 10, GE 11, the filtration coefficient is recommended to be less than 0.001 m / day.

In hydrogeological terms, the construction site as a whole is characterized by the absence of groundwater, however, during the period of additional engineering and geological surveys (June 2019), the presence of groundwater of a sporadic distribution of the top water ("verkhovodka" in russian) type was established (drilled in well No. 2 on depth of 1.80 m (absolute elevation 19.88 m)), which are confined to modern Quaternary technogenic formations (tIV). Groundwater is fed by infiltration of atmospheric precipitation. Unloading is carried out in the river Izhora, which flows 60.0 m south of the extreme point of the site. It was found that during the surveys on the slope, folded with fill soils, gullies were found, along which water seeps out.

The specific soils in the investigated area, according to the data of the studies carried out and according to SP 11-105-97, Part III, include compacted bulk soils (GE 1).

The normative depth of seasonal freezing for fill soils (GE 1) is 1.28 m; for clays (GE 10b, 10, 11) – 0.98 m. According to the degree of frost heaving, in accordance with SP 22.13330.2011, p. 6.8.8, fill soils (GE 1) refer to heapy soils (D ≥ five); according to the degree of frost heaving (according to the parameter R_f and the relative deformation of heaving ε_{fh}), semi-hard clays, dislocated (GE 10b) – ($R_f = 0.21$, $\varepsilon_{fh} = 0.02$) refer to slightly heaving soils; hard clays, dislocated (GE 10) – ($R_f = 0.64$, $\varepsilon_{fh} = 0.05$) refer to medium-porous soils; hard clays (GE 11) – ($R_f = 0.78$, $\varepsilon_{fh} = 0.06$) refer to medium-heap soils.

Note that during periods of the year with negative temperatures, frost heaving processes occur in soils, which can be considered as one of the potential reasons for a decrease in the strength characteristics of the boundary layer of dislocated clays. In combination with the soaking of this layer, a sharp decrease in the strength and deformation characteristics of the soil, a change in its consistency, is possible, which, when a load is applied during the embankment, caused the development of uneven deformations of the bridge support No. 10L.

2. NUMERICAL SIMULATION OF THE CHANGE OF STRESS-STRAIN OF THE BASE OF SUPPORT NO. 10 L AT SLIDES SOIL PRESSURE

Modeling of the geotechnical situation in order to predict the further development of deformations of the structures of support No. 10L was carried out numerically in the certified software Plaxis 3D in a three-dimensional formulation from the condition of the installation of vertical and inclined drill-injection piles with a diameter of 300 mm with reinforcement with a metal pipe diameter 159 mm (Figures 6 and 7).

The mechanical behavior of soils in the calculation was modeled by an ideal elastoplastic Mohr - Coulomb model.

Based on the results of numerical modeling, the horizontal displacements of support No. 10L were determined. The standard and calculated values of

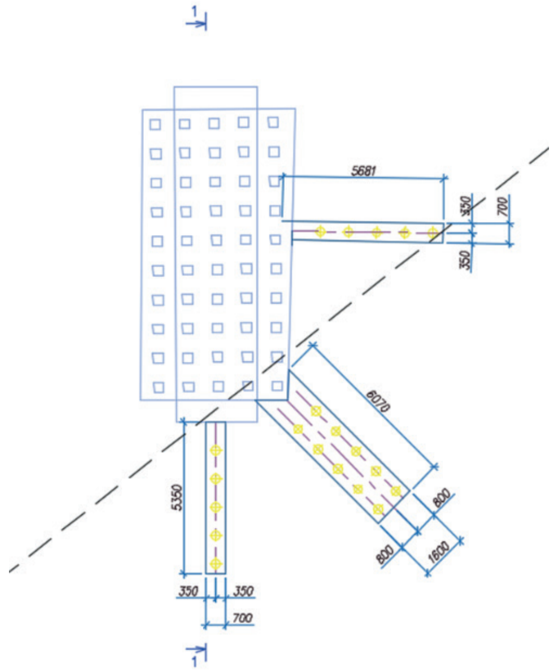

Figure 6. Layout of retaining structures

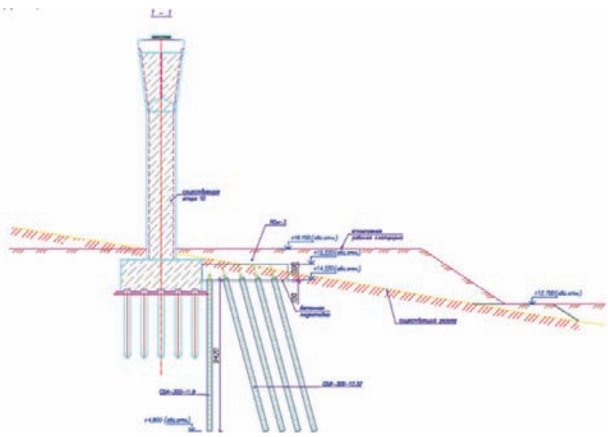

Figure 7. Sectional view of retaining structures

Table 1. Physical and mechanical characteristics of soils

№ ИГЭ	Soil type	geological index	Soil density, g / cm³			porosity coefficient	natural moisture	plasticity index	Liquid limit	Strength characteristics						deformation modulus МПа	Comment
										Internal friction angle [°]			Cohesion МПа кгс см$^{-2}$			кгс см$^{-2}$	
			ρ_n	ρ_{II}	ρ_I	e	W_e	I_p	I_L C_b	φ_n	φ_{II}	φ_I	C_n	C_{II}	C_I	E	
1	Bulk soils not packed	t IV	R_0 = 0,08 МПа (0,8 кгс см$^{-2}$)														R - SP 22.13330. 2011, Appendix B, table. B.9
106	semi-solid clays, dislocateded	ϵ_1	2,01	2,01	2,00	0,748	0,263	0,227	0.00 -	11	11	10	0.077 0,77	0.077 0,77	0.051 0,51	9 90	O, C, E - laboratory data
10	solid clays, dislocateded	ϵ_1	2,10	2,09	2,08	0,607	0,211	0,216	-0.39 -	14	13	12	0.110 1,10	0.101 1,01	0.095 0,95	15 150	O, C, E - laboratory data
11	solid ttclays	ϵ_1	2,15	2,14	2,13	0,522	0,184	0,198	-0.41 -	15	15	14	0.169 1,69	0.156 1,56	0.147 1,47	22 220	O, C, E - laboratory data

the characteristics of the physical and mechanical properties of soils adopted for the calculation are presented in Table 1.

The calculation simulated three phases:

1) modeling the initial stress-strain state (SSS), formed by the own weight of the soil mass;

2) installation of piles and supports No. 10L at the construction site;

3) the transition of the soil into a landslide state due to waterlogging of the soil massif of the slope (liquefaction landslide), through a change in the characteristics of the soil, in order to obtain deformations consistent with field observations;

3.1) forecast of final deformations of support No. 10L without taking into account measures to strengthen the foundations;

3.2) forecast of the final deformations of the support No. 10L taking into account the structure of the reinforcement in the form of a buttress on the bore-injection piles.

In order to prevent further development of horizontal displacements of supports and embankments, the following solution was proposed: to arrange vertical and inclined piles, united by a monolithic growth-vertex in the form of three buttresses along the perimeter of the support, located in the direction of deformation development (at the corner point of the support grillage No. 10L to the river), along the main passage and in the transverse direction from the river.

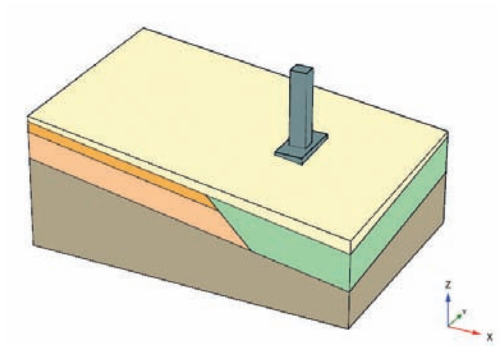

Figure 8. Model at the stage of assessing the impact of the occurrence of the landslide effect of the foundation soils (the load on the support is 2000 t). The UPPER soil at the support is conventionally hidden, for visual display of the buttress)

Table 2. Information about loads

Support	Point	Dead load			Live load		Total	
		Normative	Design, min	Design, max	Design, min	Design, max	min	max
No. 10 L	10.1	513	461	611	-39	311	422	922
	10.2	597	537	705	-39	310	498	1015

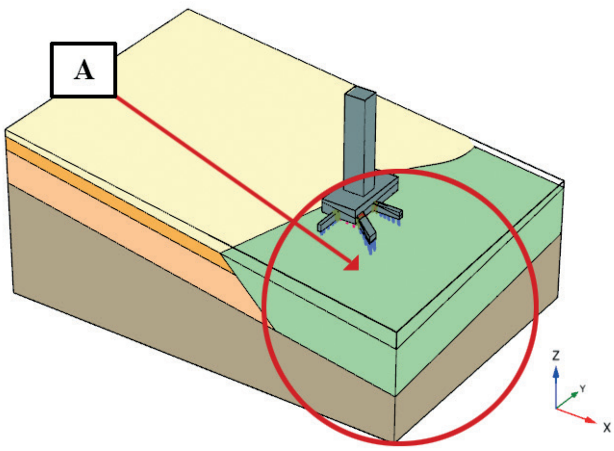

Figure 9. Design model taking into account the reinforcement of existing foundations with a buttress

Figures 6 and 7 show the layout of the retaining structures.

Figure 8 shows the design model at the stage of assessing the impact of the occurrence of the landslide effect of the foundation soils.

In order to eliminate the rigid connection between the buttress and the existing grillage, special finite elements "Interface" are introduced, which simulate the contact between two materials. The parameter Rint is introduced into them, which in our problem is taken to be 0.01, which corresponds to the complete absence of friction on the surface (Fig. 9). Calculations were made according to the design solution without taking into account the change in soil properties. Deformation schemes and calculation results are presented in Figures 11 and 12.

In general, the results for this phase of the calculation showed that the deformations of the support No. 10L when the design loads are applied do not exceed the limit values equal to 20 cm, but indicate the unevenness of the support deformations. In this case, the maximum horizontal deformation falls on the displacement of the top of the support (direction perpendicular to the axis of the bridge). All this Data on the loads acting on the support were taken in accordance with Table 2.

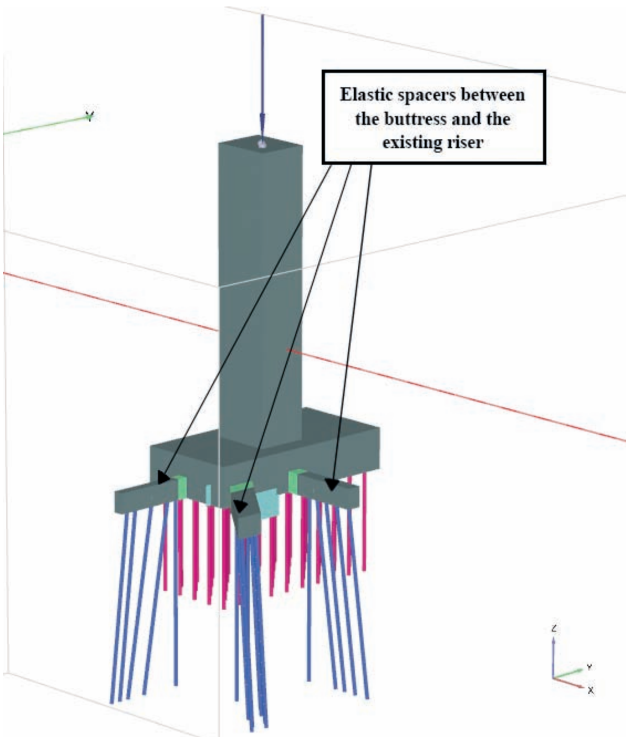

Figure. 10. Enlarged node A

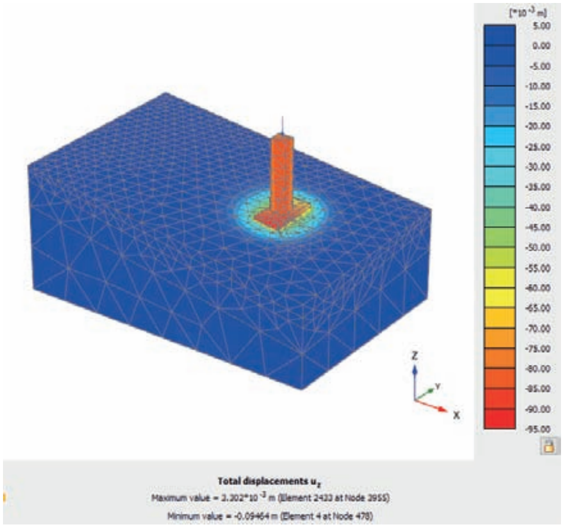

Figure 11. Vertical deformations of the support when a load of 2000 t is applied.

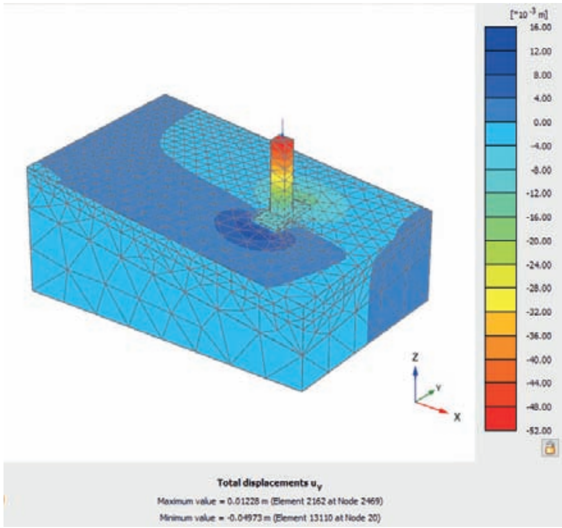

Figure. 13. Horizontal deformations of the support along the Y axis (equal to 49.7 mm) when a load of 2000 t is applied

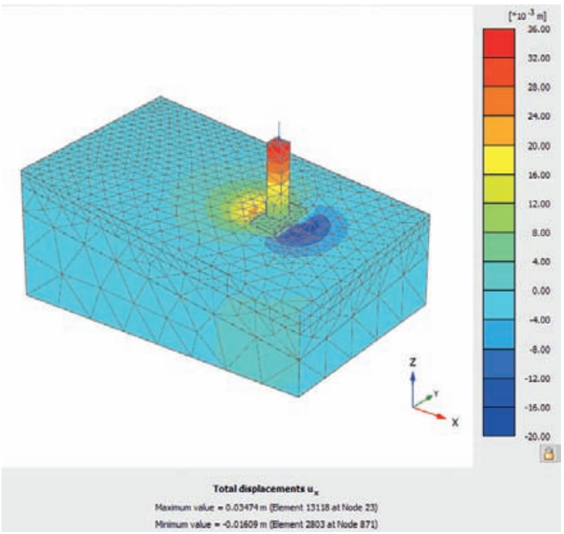

Figure. 12. Horizontal deformations of the support along the X axis (equal to 34.7 mm) when a load of 2000 t is applied.

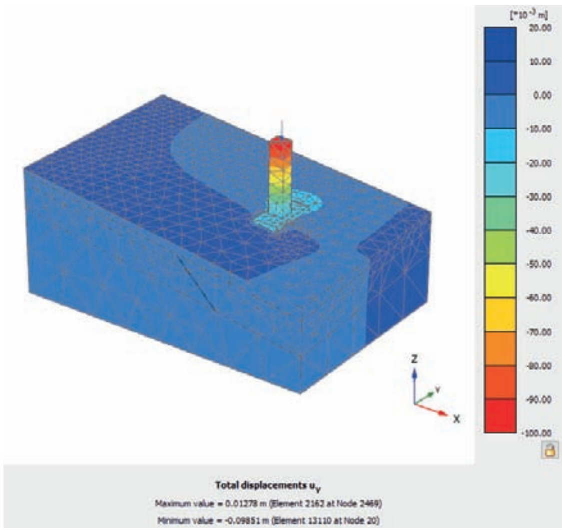

Figure. 14. Horizontal deformations of the support along the Y-axis (- 9.85 cm) according to the actual situation

All this testifies to the correctness of the implemented design solutions in the absence of factors influencing the development of slope landslide processes and soaking of the soils of the base of support No. 10L.

Given the inconclusive nature of the deformations and the certain dynamics of their development, for the analyzed support No. 10L, it is possible, with subsequent numerical modeling, to predict the final deformations of the support, which are presented below (Figures 15–17). For this purposes, two types of calculations were carried out.

1) Forecast of the final deformations of the support No. 10L excluding reinforcement measures

According to numerical modeling, the expected final deformations of the support under the action of landslide soil pressure are expected to be as follows: vertical deformations taking into account soaking will be 16.09 cm, horizontal deformations of the support along the X and Y axes, respectively, 21.75 cm and 12.49 cm.

Thus, the expected final deformations of the support according to numerical modeling exceed 20 cm, predetermining the need to strengthen the soils around the support No. 10L in order to stabilize its deformation under the influence of design loads and taking into account the actual state of the soils at the base of the support.

Further, the design verification of the solution to reinforce the existing foundation with buttresses was carried out in order to stabilize the displacement of the support No. 10L.

2) Forecast of the final deformations of the support No. 10L, taking into account measures to strengthen

In order to take into account the fact that the counter-force structures will be erected during the landslide movement of the soil, they were activated in the phase where the characteristics of the soil deteriorate, which, as it seems, most accurately reflects the actual situation.

Thus, calculated taking into account the proposed reinforcement, the magnitude of horizontal deformations showed a decrease of 1.36 times, which indicates the effectiveness of the proposed reinforcement design.

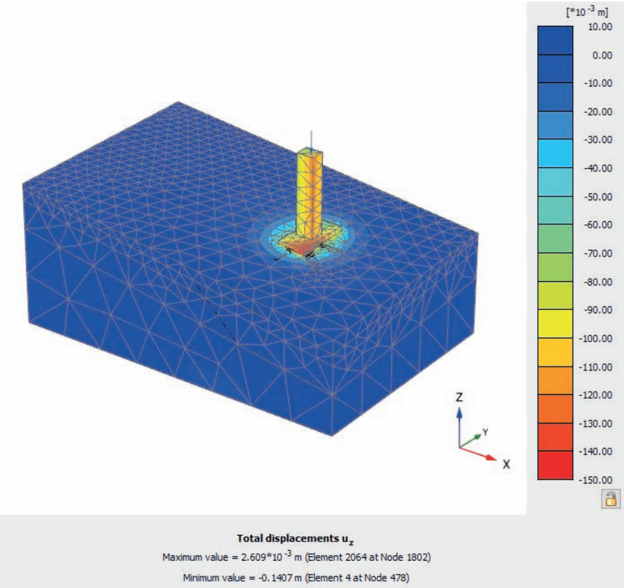

Figure. 15. Vertical deformations of the support No. 10L taking into account the reinforcement (-14.07 cm)

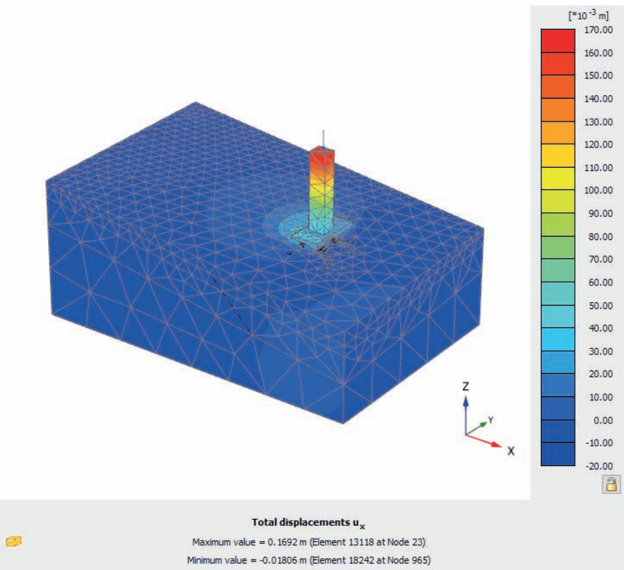

Figure. 16. Horizontal deformations of the support taking into account the X-axis reinforcement (-16.92 cm)

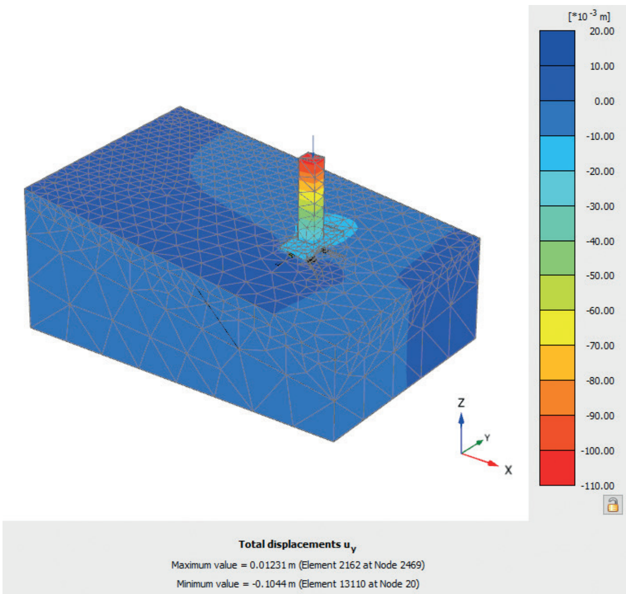

Figure. 17. Horizontal deformations along the Y-axis (- 10.44 cm) taking into account the amplification.

CONCLUSIONS AND RECOMMENDATIONS

The conducted research allows us to formulate the following conclusions:

a) the results of the verification calculation indicate the correctness of the implemented design solutions in the absence of factors affecting the development of slope landslide processes and soaking of the soils of the base of support No. 10L;

b) the deformations revealed by the monitoring results arose due to the development of the landslide process of the coastal slope due to waterlogging of the soil massif and soaking of the soil at the base of support No. 10L, as a result of which there was a change in the physical and mechanical properties of soils at the base of the slope around the support. At the same time, it is noted that construction processes carried out in the immediate vicinity of the support served as a trigger for the occurrence of deformations;

c) the horizontal deformations obtained in the actual state of the soils at the base of the support in the directions of the bridge axis and perpendicular to the axis of the bridge indicate the need to perform soil stabilization work at the base of the support and a structural reinforcement device in the form of buttresses to prevent further deformation of the bridge support;

d) numerical modeling, taking into account the arranged buttresses of the reinforcement of the support No. 10 L of the bridge, additional horizontal movement along the axis of the bridge will be no more than 15.8 mm (1.58 cm). According to the above calculation, in the piles of the buttress structure, the maximum forces of 184 kN occur;

e) comparison of the results of numerical modeling and observations showed the absence of stabilization of deformations without additional constructive measures to fix the support from deformation and injection anchoring of waterlogged soils of the support base.

Based on the foregoing, priority measures were developed and implemented to eliminate deformations of support No. 10L and to ensure soil stabilization of the base of support No. 10L of the bridge across the river Izhora:

– fixing the support with the device of buttresses in the direction of its displacement, in the direction of the axis of the bridge and in the transverse direction of the axis of the bridge, followed by stabilization of the soil at the base of the embankment to exclude its subsequent deformations. It is proposed to fix the support by creating buttresses on a pile foundation: piles – vertical and inclined, five pieces for each buttress in the transverse and longitudinal directions with respect to the axis of the bridge and a doubled number – 10 piles in the buttress – in the direction of movement of the support (corner part of the support). The buttresses to be built are connected by a monolithic grillage. In the contact plane of the buttress structure, to fix the support and the grillage of the pile foundation of the support, fluorine-layer gaskets were installed over the entire contact area of the structures;

– to stabilize the soil massif at the base of support No. 10L, it is recommended to perform soil improvement using injection methods or soil mixing. A prerequisite for the normal design operation of the slope is the exclusion of the subsequent soaking of soils at the base of the support and the slope by means of an annular drainage device along the slope and near support No. 10L;

It was proposed to continue regular geotechnical monitoring of precipitation and deformation in the soil massif according to the approved program. The criterion for permissible additional deformations can be taken as 16 mm, obtained from the calculation results.

REFERENCES

1. Building Code of Russia SP 34.13330.2012 «SNiP 2.05.02-85*Avtomobil'nyye dorogi». [Highways]
2. Building Code of Russia SP 35.13330.2012 «SNiP 2.05.03-84 Mosty i truby». [Bridges and pipes]
3. Building Code of Russia SP 22.13330.2016 «SNIP 2.02.01-83*Osnovaniya zdaniy i

sooruzheniy». [Foundations of buildings and structures]
4. Building Code of Russia SP 24.13330.2011 «SNiP 2.02.03-85 Svaynyye fundamenty». [Pile foundations]
5. Building Code of Russia SP 45.13330.2017 «SNiP 3.02.01-87 Zemlyanyye sooruzheniya, osnovaniya i fun-damenty». [Earthworks, foundations and foundations]
6. Building Code of Russia SP 46.13330.2012 «SNiP 3.06.04-91 Mosty i truby». [Bridges and pipes]
7. Building Code of Russia SP 47.13330.2016 «SNiP 11-02-96 Inzhenernyye izyskaniya dlya stroitel'stva. Osnovnyye polozheniya». [Engineering surveys for construction. Basic provisions]
8. Building Code of Russia SP 274.1325800.2016 Mosty. Monitoring tekhnicheskogo sostoyaniya. [Bridges. Monitoring of technical condition]
9. Building Code of Russia SP 305.1325800.2017 Zdaniya i so-oruzheniya. Pravila provedeniya geotekhnicheskogo monitoringa pri stroitel'stve. [Buildings and facilities. Rules for conducting geotechnical monitoring during construction]
10. **Mangushev R.A., Osokin A.I., Sotnikov S.N.** Geotekhnika Sankt-Peterburga. Opyt stroitel'stva na slabykh gruntakh : Monografiya [Geotechnics of St. Petersburg. Construction experience on soft soils]. – Moscow: Publishing ASV, 2018. – 386 p.
11. **Mangushev R.A., Yershov A.V., Osokin A.I.** Sovremennyye svaynyye tekhnologii : Uchebn. Posobiye [Modern pile technologies]. 3-rd edition, remastered and added. – Moscow: Publishing ASV, 2010. – 240 p.
12. **Mangushev R.A., Gotman L.A., Znamenskiy V.V., Ponomarev A.B.** Svai i svaynyye fundamenty. Konstruktsii, proyektirovaniye i tekhnologii [Piles and pile foundations. Constructions, design and technology] / under editorship R.A. Mangushev – Moscow: Publishing ASV, 2015. – 320 p.
13. Spravochnik geotekhnika. Osnovaniya. Fundamenty i podzemnyye sooruzheniya [Handbook of geotechnics. Foundations. Foundations and underground structures]. 2-nd edition, under general editorship V.A. Il'ichev and R.A. Mangushev.- Moscow: Publishing ASV, 2016 – 1040 p.

СПИСОК ЛИТЕРАТУРЫ

1. СП 34.13330.2012 «СНиП 2.05.02-85*Автомобильные дороги».
2. СП 35.13330.2012 «СНиП 2.05.03-84 Мосты и трубы».
3. СП 22.13330.2016 «СНИП 2.02.01-83*Основания зданий и сооружений».
4. СП 24.13330.2011 «СНиП 2.02.03-85 Свайные фундаменты».
5. СП 45.13330.2017 «СНиП 3.02.01-87 Земляные сооружения, основания и фундаменты».
6. СП 46.13330.2012 «СНиП 3.06.04-91 Мосты и трубы».
7. СП 47.13330.2016 «СНиП 11-02-96 Инженерные изыскания для строительства. Основные положения».
8. СП 274.1325800.2016 Мосты. Мониторинг технического состояния.
9. СП 305.1325800.2017 Здания и сооружения. Правила проведения геотехнического мониторинга при строительстве.
10. **Мангушев Р.А., Осокин А.И., Сотников С.Н.** Геотехника Санкт-Петербурга. Опыт строительства на слабых грунтах : Монография. – М.: Изд-во АСВ, 2018. – 386 с.
11. **Мангушев Р.А., Ершов А.В., Осокин А.И.** Современные свайные технологии :Учебн. пособие. 3-е изд., перераб. и доп. – М.: Изд-во АСВ, 2010. – 240 с.
12. **Мангушев Р.А., Готман Л.А., Знаменский В.В., Пономарев А.Б.** Сваи и свайные фундаменты. Конструкции, проектирование и технологии/ Под ред. Р.А. Мангушева – М.: Изд-во АСВ, 2015. – 320 с.
13. Справочник геотехника. Основания. Фундаменты и подземные сооружения: издание второе, доп. и перераб. / Под общей ред. В.А. Ильичева и Р.А. Мангушева. – М.: Изд-во АСВ, 2016. – 1040 с.

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STRENGTH ANALYSIS IN DESIGN CODES AND SOFTWARE

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Abstract. Modern building design standards have a long history. During this time, they have undergone a number of changes, but some of their provisions and recommendations, once proclaimed, remain unchanged. And although they do not meet the modern possibilities of computational analysis, but continue to exist due to the established tradition. In this paper, attention is paid to only some of the mentioned conflicts, which are related to the software implementation of regulatory requirements.

Keywords: load-bearing capacity, building codes, computer analysis

ПРОЧНОСТНОЙ РАСЧЕТ В НОРМАХ ПРОЕКТИРОВАНИЯ И В ПРОГРАММНЫХ СИСТЕМАХ

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Аннотация. Современные нормы строительного проектирования имеют уже довольно длинную историю. За это время они претерпели ряд изменений, но некоторые их положения и рекомендации, будучи раз провозглашенными, остаются неизменными. И хотя они не соответствуют современным возможностями расчетного анализа, но продолжают свое существование в силу сложившейся традиции. В этой работе обращается внимание лишь на некоторые из упомянутых коллизий, связанных с программной реализацией нормативных требований.

Ключевые слова: несущая способность, строительные нормы, компьютерный анализ

INTRODUCTION

The experience of design activity in recent decades shows that the development of automation of engineering calculations has the most serious impact (unfortunately, both positive and negative) on the quality of justifications for design decisions. The level of detail and accuracy of calculation, which is now available to designers en masse, yesterday was still unattainable even for the most qualified organizations and professionals. At the same time, the availability of modern powerful computing systems creates a number of new problems. One of them is the growing number of inconsistencies between the capabilities of software systems, which are focused on a detailed analysis of the work of structures, and the requirements of regulations, which are focused on established experience.

Almost all modern tools of building design automation implement to some extent the requirements of existing regulations. At the same time the inclusion of regulatory requirements in software systems is not only a problem of their developers, but also a problem of a wide range of users. The point is that users have to understand which requirements for regulatory documents can and should be imposed on the relevant software, when deciding on its use. An almost complete disarray takes place here today. Some users would like everything to be implemented (including departmental, company and other detailed instructions), others would like the developers to allow them to decide which rules should be followed and which can be ignored, still others want detailed references to justify regulatory requirements and etc.

Of course, one can rely on the following principle. The implementation of regulatory requirements in the software must strictly adhere to the text of the regulatory document. In cases where this is not possible in general (examples of such a situation are given below), the program should refuse to perform the appropriate function in the part that does not adequately reflect norms, notifying the user. In this case, an accurate reflection of possible limitations of this kind in the program documentation should be a prerequisite.

Another set of problems is due to the fact that modern software systems focus on the use of universal provisions of such disciplines as the theory of elasticity, the theory of plasticity, structural mechanics, etc. while some provisions of the norms are based on simplified approaches, test results and experience of operation of existing structures. But being presented in the regulatory document, such provisions suddenly take advantage over scientifically sound and more accurate solutions, which do not appear in the codes only due to the complexity of calculations. Almost all modern tools of construction design automation implement to some extent the requirements of existing regulations. Meanwhile there are certain problems of technical, legal and economic nature, which often arise due to the fact that the developers of regulations did not forecast the possibility (and necessity!) of their software interpretation.

TWO INTERPRETATIONS OF THE CONCEPT OF "CALCULATION OF STRUCTURES"

The design justification of design decisions is a multi-stage process, in which, at least, two main parts should be distinguished: calculation of the stress-strain state (SSS) and verification of the accepted cross sections (or their reinforcement). Unfortunately, this fact is not emphasized and when talking about the calculation of structures is not always clearly stated what we are talking about.

At the same time from the point of view of rationing the differences here are fundamental: the calculation of SSS is the problem of structural mechanics and this process in principle should not be the subject of rationing, while checking the bearing capacity of sections is a conditional procedure aimed at achieving a certain degree of safety. The rationing, i.e. the establishment of certain requirements of society, is quite appropriate here.

Returning to the stage of the SSS calculation, we can say that only some "permitting procedures", which establish acceptable simplifications of the problem, can be controlled by the design code. It is important to note here that it is a question of allowable simplifications, instead of their obligatory application though in texts of regulatory documents this fundamental difference is not stipulated in any way. The question arises here about the inequality of the results of the simplified calculation performed in accordance with design standards and the possible result of a more accurate analysis.

It should be noted that modern software systems often have the ability to perform the structure calculation in much more detail and accuracy than required by regulations. Such details of the stress-strain state and such details of the behavior of the structure under load can be found, which were not taken into account by the authors of the normative document or, more often, taken into account in the design standards by applying some special coefficient of working conditions or other ways to take into account additional bearing capacity. Since these techniques are not deciphered in detail in the regulations, the corresponding feature may be taken into account twice: the first time in the framework of computer simulation and the second time in the regulatory verification, which is performed using the above additional coefficient. As a result (and this has happened many times) a project with a more thorough calculation justification will be less economical than a rougher calculation according to the standards.

The situation may be even more complicated when the normative document provides for a calculation procedure in which some empirical correction factors are used. A typical example is the standards for seismic analysis of structures [3], where the results of the response specrtum method are adjusted by the reduction factor K1, which is introduced to take into account the plastic behavior and local damage. Since the degree of plasticization of structural elements and the amount of local damage is not specified, it remains unclear what to look for when using other methods of calculation (direct integration of equations of motion, deformation method of checking the ultimate forces, etc.).

Another example is the calculation for temperature effects. The fact is that the design standards of structures set the maximum distances between the temperature seams (see, for example, section 15.1 of the Russian construction code SP 16.13330.2017 [5]). Traditionally, it is considered that the calculation of temperature effects can be omitted when a compartment length does not exceed these limits. But it has been repeatedly detected that such a calculation leads to the conclusion of a significant overstrain of the load-bearing structures, which causes surprise and numerous discussions.

The discovered contradiction is due to the fact that the standard calculation models of force calculation do not take into account some flexibility of the nodal joints (for example, slippage of the base of the steel column on the foundation within the black holes for anchor bolts). Such shifts, which are absolutely insignificant under force loading, are decisive under the kinematical influence of the thermal deformation type. Their values may be compared with thermal elongations and they dramatically affect the stress-strain state. Here, the rules, which are based on many years of practical experience, are "smarter" than traditional analysis.

Thus, it can be stated that if the calculation model adopted for computer analysis of the structure does not correspond to the model that was meant when compiling the regulatory document, there may be contradictions or inaccuracies that cannot be resolved without decoding the approach adopted in the standards. Unfortunately, such a decoding is not provided in our rationing system.

ON REGULATION OF CALCULATION METHODS

Although the science of "structural mechanics" can not set standards, if we keep in mind the methods and rules of calculation, but when it comes to choosing a calculation model, the question is not so clear.

The fact is that the design standards are a chain of trade-offs, where some inaccuracies in the calculation of some parameters (e.g., internal efforts in the system) are offset by safety factors embedded in other parameters (e.g., in the design strength). In addition, the method used by the authors of the rules can be based on a certain calculation model, and this model occurs to be specified in the normative document.

Traditionally, building design standards have focused on certain set of calculation schemes. Most often, these were plane bar systems loaded in one plane or in mutually orthogonal planes and operating in a uniaxial stress state. Spatial structures, especially of shell type, are considered much less often. However, they are almost standard when calculating using software. And here there is a certain imbalance of possibilities, when many cases, normalized for traditional calculations, are simply absent for the calculations of spatial systems.

As an example, let us mention the fact that the design standards for steel and reinforced concrete structures provide a material stress-strain diagram only for uniaxial state and there are no recommendations for assessing the performance of structures in 2D or 3D stress state. In this case, the normative documents on the design of reinforced concrete structures, which are calculated by a nonlinear deformation model, for example, are focused on checking the values of ultimate deformations, but such criteria are given only for uniaxial stress state. How they should be transformed with respect to the 2D stress state is completely unclear. After all, there is no theoretical justification for the use of deformation criteria here. Moreover, any theory of plasticity is based on the concept of the boundary surface in the stress space, whereas the concept of the boundary surface in the space of deformations simply does not exist.

Another problem concerns the interpretation of the results of the spatial calculation model analysis in accordance with the regulatory documents. So, for example, for bar elements we receive six internal forces and N, M_x, Q_y, M_y, Q_x, M_z instead of three N, M, Q and even if any element works "in plane" that nonzero values (probably small on size) can have all six internal forces. How small must be certain forces, so that they can be neglected, is not specified.

For example, the concept of a beam used in [5] and [4], obviously implies the ability to neglect the influence of longitudinal force in comparison with the influence of moments. But if in the first case for steel structures in 9.2.2 there is a record that for the value of the given relative eccentricity m_{ef} > 20 the calculation can be performed as for the bent element (i.e. to neglect the influence of longitudinal force), then for reinforced concrete structures such idealization is not defined. And for steel structures, the limit m_{ef} = 20 is specified to test the stability, and whether this recommendation of standards allows a common interpretation is unknown.

Of course, a competent engineer can determine this limit in each case, but some rule is required for the software implementation, and its absence creates a situation for unnecessary controversy.

The above is a fairly typical situation when the normative document contains some information (for example, tabular values), but in the program it is more profitable to calculate them than to borrow it from the table. What degree of disagreement is permissible (or non-existent) is the subject of many meaningless discussions. But the requirements of design norms are not laws of nature, they only approximate these laws with one or another degree of accuracy. Unfortunately, information about the errors that are permissible according to regulatory documents can be found nowhere. The only exception that can be found is the use of 10.0 instead of the exact value of the acceleration of gravity 9.81 when converting the normative values of loads from kPa in kgf / m^2 in building regulations SNiP 2.01.07-85* of 1985 edition or 0.1 instead of $1/\pi^2$ in the formula (108) of building rules SP 16.13330.2017.

The problem of joining results at conditional borders is connected with the delimitation of basic concepts. Since some simplifying hypotheses were used in various variants of the stress-strain state, belonging to one or another category of normalization (compressed-bent bar, bent beam, etc.), it is often difficult to implement a smooth border crossing.

Especially many problems are connected with necessity (possibility, desirability?) of performance of the general static calculation taking into account geometrical and physical nonlinearity declared by standards.

However, the following question remains unclear. Is it possible to apply the results of the calculation which was performed taking into account geometry changes if it concerns the coefficient of longitudinal bending φ? This coefficient is of great importance for the stability of compressed steel rods analysis and calculated using deformed model (but for the element, not entire system).

PROBLEMS THAT CANNOT BE SOLVED WHEN USING NONLINEAR CALCULATION

For a number of computational cases that inevitably arise in the actual design, regulations establish rules necessarily requiring a linear approach to solving the problem. An example is dynamic analysis closely related to such concepts of linear dynamics of structures as the frequency and mode of the natural vibrations of the system. For a nonlinear system, the very concept of individual forms of natural oscillations disappears and all recommendations based on this (i.e. the procedure of decomposition of motion into a superposition of normal modes) lose their meaning.

An alternative approach suitable for accounting for nonlinear effects is sometimes (though rarely) present in standards, such as direct dynamic calculation by instrumental or synthesized accelerograms, but more often it is not only not mentioned, but simply not developed. Analysis of the response to the pulsating wind loadings can be typical here.

Another problem that is not solved in the nonlinear analysis is the problem of choosing unfavorable load combination. In practice, there are virtually no structures that work only on one load option. It is usually necessary to anticipate the possibility of the occurrence of many temporary loads and, therefore, it is necessary to somehow determine their estimated combination. This problem has a solution with a linear approach to the calculation, when you can use the principle of superposition. If you focus on nonlinear analysis, then at the same time you should specify for which combination of loads you should perform strength and stability analysis. This type of instructions in regulations is often missing.

STABLE EQUILIBRIUM

Examination of the equilibrium stability of the complex bar type structure in the general case requires the calculation accounting the geometric nonlinearity and inelastic operation of the structural elements. Calculation of this type, in addition to computational complexity, also requires overcoming a number of other difficulties associated with the great uncertainty of the design assumptions (patterns of load change, idealization of material properties, initial irregularities, residual stresses, etc.). In this regard, in engineering practice there is a tradition of performing an idealized elastic calculation of the stability of the system as a whole in combination with checking individual elements for which more detailed account of the inelastic behavior of the material, initial bends and eccentricities and other circumstances is performed.

Most often, the stability problem is replaced by a refined calculation of the deformed model with increasing bending moments in compressed bars or other similar way by multiplying by some buckling length coefficient φ or coefficient of bending moments increasing $\eta = 1 / (1\text{-}N / N_{cr})$. The critical value (in the sense of loss of stability) of the value of compressive force takes part in the choice of the value of these coefficients and this fact ties the calculation of the deformed model to the stability analysis of the idealized model.

A natural question arises about the relationship between these two approaches. To what extent and for what purposes can their results be used separately and what is the link between them? It is believed that the bridge that combines these two approaches will be the buckling lengths of the elements of the system. Therefore, the fundamental question is of the method of determining the buckling lengths.

Note also that the use of the concept of buckling length involves the division of bar type systems into separate elements, it is necessary to take into account the interaction of the element with the foundation and other elements (primarily adjacent to it in the nodes).

The logic of most of the standards recommendations is focused on flat computational models or, at least, on a separate consideration of the spatial scheme in two orthogonal planes. If we turn to spatial systems, they may have difficulties of a completely different kind, associated with the use of the concept of flexibility in the two orthogonal planes of inertia of the bar element.

Following the classical approach of F.S. Yasinski [10], the buckling length of the bar is usually understood as the conditional length f a simple bar, the critical force of which when hinged its ends is the same as for a given rod. In terms of physical content, the buckling length of the bar with arbitrary fixings is the largest distance between two inflection points of the bent axis, which are determined from the stability analysis of this bar by the Euler method.

In the works of Yasinski himself and in numerous subsequent works, where the concept of the buckling length of the bar appears, the use of plane calculation models and, accordingly, plane deformation models is implicitly implied. Only for them it makes sense to consider the distance between the inflection points of the curved axis, taken as the calculated length.

Since even for plane models, the buckling length of compressed bars should be determined both in the plane and from the plane of the system, then here there is a mismatch with the definition of F.S. Yasinski. Indeed, imagine a spatial cantilever bar in which the cross section has moments of inertia J_x and $J_y = 4J_x$. Under central compression, such a bar loses stability under load $P_{cr,x} = \pi^2 EJ_x./(2l)^2$ ($l_{ef,x} = 2l$).

From the point of view of standards, apparently, it is possible to imagine a situation when two calculations on stability are performed during which deformation in one or in another main plane of inertia is alternately forbidden (for example, considering that $J_x = \infty$ and then $J_y = \infty$) , and after that the coefficients of the buckling length μ_x and μ_y are determined. But, as far as we know, for any complex systems, such even calculations in design practice are not performed.

Other problems arise when in the spatial system the main axes of inertia of the elements are not parallel to each other and the mode of stability loss, as well as the free lengths, is dependent on the orientation of these axes.

A fairly typical example is shown in Fig. 1, which shows the modes of stability loss and values of critical loads for two structures, which differ in that the cross-sections of the struts have different orientations of the main axes of inertia.

The model showed in Fig. 1 (a) has the coefficient of the buckling length in the plane of minimum rigidity μ_x = 0,597, while the model showed in Fig. 1 (б) has μ_x = 0,523. In the first case, the loss of stability mode is such that all the column are deformed in the plane of least rigidity. In the second case such deformation is observed only in two columns while the other two are deformed in the plane of greatest rigidity.

It should be noted that the solution of F.S. Yasinski refers to an elastic centrally compressed bar of constant cross-section, which when lost stability buckles in the form of a plane curve. Since the magnitude of the free length does not depend on the transverse load and is determined only by boundary conditions, this concept has been extended to elastic eccentrically compressed elements that bend in one of the main planes of inertia. Therefore, the in plane bending is

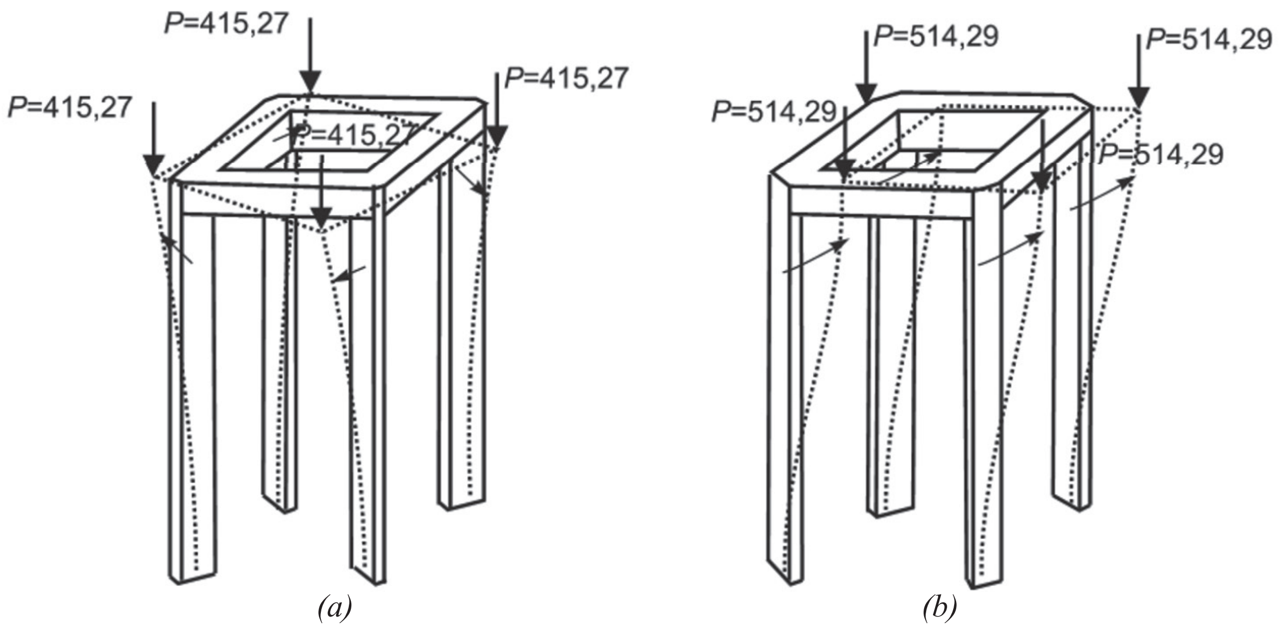

Figure. 1. Sample of analysis

implicitly assumed, because only in this case it makes sense to consider the distance between the inflection points of the bent axis, taken as the buckling length.

However, even a single bar can lose stability by having a spatial bending curve that occurs, for example, when the ends of the bar have cylindrical hinges whose axes are not parallel to each other. Another example that limits the scope of the classical concept of the buckling length is the case of the torsional mode of stability loss. A number of other examples that indicate the difficulties arising here are given, for example, in [6].

However, the convenience of using the concept of the buckling length has made this method extremely popular, in almost all countries it is included in the regulations governing the verification of the bar structures equilibrium stability.

The buckling length of the elastic bar was used for normative calculation in the inelastic stage of the bar loading. It should be recognized that there is, in fact, no clear theoretical justification for this, and it should be considered a heuristic technique. And the widespread use of this technique is most likely due to the fact that engineers needed at least some practical method of calculating the bar structures for stability. Therefore clarity, associated with the solution of the simplest problems, replaced the reasoning of accuracy.

DYNAMIC CALCULATIONS

Almost all regulations in the field of dynamics focus on the use of decomposition into modes of natural vibrations. Thus, the use of linear equations is implicitly assumed, and only in a few cases do software systems consider the linearized behavior of a nonlinearly deformable structure, i.e. analyze small oscillations around the deformed equilibrium position.

When focusing on the eigenmode decomposition, many regulatory documents indicate the number of eigenvalue forms to be taken into account, with no indication of the calculation model used. As a result, it has repeatedly happened that the first few natural frequencies (namely they are recommended to take into account by the standards) determine the local partial modes of motion, while the main mode of deformation is not the first.

The second problem of dynamic calculations, which is often mentioned indirectly by regulations, is the excessive simplification of dynamic models. This simplification due to tradition is often perceived as a characteristic of real behavior, which can lead to misunderstandings. Thus, the long-standing habit of using the cantilever calculation model in the seismic analysis has led to the fact that the detection of torsional vibrations as one of the lower is treated as a shortcoming, although no one could indicate what is the defect of this design.

It is necessary to mention one more aspect of dynamic calculations using eigenmode decomposition. It is associated with summation of modal contributions, which often follows the well-known "root-sum-squares" (RSS) rule. But this approach is based on the hypothesis that all modal reactions are normally distributed random variables with the same correlation coefficients, which is consistent with many observations, although not an established fact. Therefore, the absolutization of the RSS rule is rather doubtful. An example is the calculation using the accelerogram in those models where the equations of motion are solved by eigenmode decomposition, and summation fulfilled according to the RSS rule. But if the integration of equations of motion is performed, for example, by the Adams method, then we come to a completely different result. Nevertheless, since one and the same problem was solved, the result should not depend on the method of its solution.

The summation of internal forces, which are calculated by the usual rules for each of the eigenmodes, is also performed by the RSS method, but there may be another disappointment. The use of modules of moments, longitudinal and shear forces leads, for example, to disappearing of compressed-bent bars, that is all of them become stretched-bent. Similar effects of sign loss are possible in shell-type elements. To overcome this phenomenon in some software systems, the total values of internal forces are assigned signs, as in similar forces corresponding to the first eigenmode. It is difficult to substantiate such an approach, even if we assume that it is the first eigenmode that realizes the main contribution to the total value of each of the components of the response vector.

ACCURACY REQUIREMENTS

Verification of compliance with structural design standards sometimes leads to uncertainties or errors due to the fact that the standards describe only one load or one stress-strain state. Detailed recommendations are given for this isolated situation, and in such a "ultimate" formulation (for example, as a calculation formula), which does not allow to understand what type of assumptions and simplifications were used. But in the real calculation it may be necessary to consider a less refined case and then there arise a number of difficulties.

As an example, we can point to the stability analysis of the plane bending of steel structures. The coefficient φ_b, the value of which is calculated in accordance with SP 16.13330.2017 and depends, inter alia, on the location of the load within the beam height of. But it may happen that the calculated combination of loads contains loads located both above and below the beam. In this case, the direct use of the rules becomes impossible.

If we take the opportunity to study the shell model of a thin-walled bar and with sufficiently detailed modeling to solve the problem of plane bending stability using the finite element method, it turns out that in the case of exact coincidence of loading options with the normative situation, we will get a solution. which does not coincide with the provisions of the design codes. This is because some approximations of exact expressions were laid down in the formulas of the appendix G [5], by means of which the coefficients φ_b are calculated. The discrepancy may be small, but the rules by which they can be considered acceptable are unknown.

What degree of discrepancy is acceptable is the subject of much nonsensical debate. But the requirements of design standards are not laws of nature, they only approximate these laws with one or another degree of accuracy. Unfortunately, nowhere can be found information about the errors that allowed by the authors of the standards. The only exception that can be found is the use of the value of 10,0 instead of the exact value of the acceleration of gravity 9,81 when translating the normative values loads from kPa to kgf / m^2 in building regulations SNiP 2.01.07-85* of 1985 edition or 0,1 instead of $1/\pi^2$ in the formula (108) of building rules SP 16.13330.2017.

The problem of permissible discrepancy of results arises when the rules have some alternatives. The developers themselves were more likely to compare the results (if any) for a "typical case", but such a comparison does not follow a good correlation of the results in any case. An example is the analysis of methods for determining the width of cracks presented in [9], when the use of different alternative solutions, allowed by the standards showed more than 59% variance of the results.

There should be some measure which allow estimate the result of the comparison. After all, in engineering calculations there is no complete coincidence of results. The generally accepted norm of similarity in the form of a five percent discrepancy must also be specified and it is necessary to know to what results (displacement, effort, etc.) and to what values (extreme, average or other) it should refer. This problem would be greatly mitigated if the comparison was conducted only by the designer. However, submitted to the experts, such comparisons will be the subject of numerous and often pointless discussions.

PROGRAMMING AS A MEANS OF CONTROLLING A REGULATORY DOCUMENT

In the pre-computer period, the vague or ambiguous recommendations, although they were evil, but this evil was not as dangerous as it is today. Today, formal compliance with the rules in the software package is hidden from the eyes of the end user, and an unambiguous interpretation of the new paragraphs of the rules is primarily needed by software developers. And these points themselves should be set out in the wording, which should be in the nature of a clearly defined algorithm of action. It seems to us that this cannot be achieved without certain organizational changes.

Software implementation of the normative document is a good test procedure, which reveals discrepancies, logical inconsistencies, incompleteness and vagueness of the formulation and other shortcomings of the draft rules, in particular, compatibility with computer methods of analysis. As an example, we can refer to the construction of the bearing area of the element taking into account the full range of proposed requirements [7, 2] which revealed some inconsistencies that lead to the rupture of the boundary and non-convexity of the permissible loads area. The construction of this area is based on the analysis of calculations that contain several hundred variants of the internal forces values. Such mass verification was simply impossible in the era of manual arithmetic.

In addition, programming reveals those aspects of the normative document that are not formulated explicitly, as the developers of the norms focused on a qualified user who can independently decide on the use of a provision, based on the specifics of the calculation situation. This is not possible for a computer program, so it will definitely be installed during programming.

It is important that such verification work is performed without the participation of the developers of the regulatory document, which would ensure the purity of the experiment.

POSSIBLE ACTIONS

How can the contradiction between the desire to develop simple and understandable design rules (traditional approach to rationing) and the ability of modern computer systems to solve problems without the use of dubious simplifications (modernist approach) be eliminated?

It seems to us that two solutions are possible here:

• develop different versions of regulations for manual and computer calculation;

• create a special regulatory and methodological document on the rules for implementing the requirements of design standards in software.

The first option can be implemented in the traditional form, when formulating general requirements and necessary hypotheses, based on which one can create a software implementation. After that there appears a text such as "allowed ...", which presents a simplified version of the standardized provision.

And in the second option, the document should reflect:

• requirements for accuracy of calculations and permissible deviations from the literal implementation of regulatory guidelines;

• the procedure for verification and coordination with the authors of the standards concerning methods of numerical solution of design problems, which expand the possibilities of verifying regulatory requirements, but not available for manual calculation;

• requirements for software developers to inform users about the peculiarities of the implementation of regulatory requirements in case of deviation from their literal implementation.

REFERENCES

1. **Bazhenov V.A., Vabishchevych M.O., Vorona Yu.V., Pyskunov S.O., Perelmuter A.V., Solodei I.I.** Kompiuterni tekhnolohii rozrakhunku prostorovykh konstruktsii pry statychnykh i dynamichnykh navantazhenniakh [Computer technologies for computation of spatial constructions under static and dynamic loadings (in Ukrainian)]. – K.: Karavela, 2018. – 312 p.
2. **Gavrilenko I., Girenko S., Perelmuter A., Perelmuter M., Yurchenko V.** Load-bearing capacity as an interactive analysis tool in SCAD Office // Proceding of the METNET Seminar 2017 in Cottbus. – Hämeelinna: HAMK, 2017. – P. 112–127.
3. Russian construction code SP 14.13330.2018 Stroitelstvo v sejsmicheskikh rajonakh [Seismic building design code]. – Moscow: Standartinform, 2018. – 122 p. (rus)

4. Russian construction code SP 63.13330.2018 Betonnye i zhelezobetonnye konstrukcii. Osnovnye polozheniya [Concrete and reinforced concrete structures. General provisions] Moscow: Minstroii Rossii, 2018. – 143 p. (rus).
5. Russian construction code SP 16.13330.2017 Stalnye konstrukcii [Steel structures]. – Moscow: Minstroii Rossii, 2017. – 145 p. (rus)
6. **Perelmuter A.V., Slyvker V.Y.** Raschetnye modeli sooruzheniy i vozmozhnost ikh analiza [Design models of structures and the possibility of their analysis (in Russian)]. – 4-e izd., pererabotannoye i dopolnennoye. – M.: SKAD SOFT, 2020. – 736 p.
7. **Perelmuter A.V., Tur V.V.** Hotovy li my pereity k nelineinomu analizu pri proektirovanii? [Are we ready to move on to nonlinear analysis in design? (in Russian)] // International Journal for Computational Civil and Structural Engineering, 2017. – Vol. 13, No 3. – C. 86–102.
8. **Perelmuter A.V., Yurchenko V.V.** Doslidzhennia oblasti nesuchoi zdatnosti tonkostinnykh sterzhnevykh elementiv iz kholodnohnutykh profiliv [Load-bearing capacity analysis of thin bar elements from cold rolled profiles (in Ukrainian)] // Nauka ta budivnytstvo, 2019, V. 21 № 3. – P. 42–48.
9. **Perelmuter M.A., Popok K.V., Skoruk L.N.** Raschet shyriny raskrytia normalnykh treshchyn po SP 63.13330.2012 [Calculation of the opening width of normal cracks according to Building Rules SP 63.13330.2012 (in Russian)] // Beton i zhelezobeton, 2014, № 1. – P. 21–22.
10. **Yasynskiy F.S.** Izbrannye raboty po ustoichivosti szhatykh sterzhnei [Selected works on the stability of compressed bars (in Russian)]. – M.-L.: Gostekhyzdat,1952.

СПИСОК ЛИТЕРАТУРЫ

1. **Баженов В.А., Вабищевич М.О., Ворона Ю.В., Пискунов С.А., Перельмутер А.В., Солодей И.И.** Компьютерные технологии расчета пространственных конструкций при статических и динамических нагрузках. Киев: Каравелла, 2018. 312 с. (на украинском)
2. **Gavrilenko I., Girenko S., Perelmuter A., Perelmuter M., Yurchenko V.** Load-bearing capacity as an interactive analysis tool in SCAD Office // Proceding of the METNET Seminar 2017 in Cottbus. Hämeelinna: HAMK, 2017. – P. 112–127.
3. СП 14.13330.2018 Строительство в сейсмических районах. Актуализированная редакция СНиП II-7-81*. М.: Стандартинформ, 2018. 122 с.
4. СП 63.13330.2018 Бетонные и железобетонные конструкции. Основные положения. СНиП 52-01-2003. М.: Минстрой России, 2018. 143 с.
5. СП 16.13330.2017 Стальные конструкции. Актуализированная редакция СНиП II-23-81*. М Минстрой России, 2017. 145 с.
6. **Перельмутер А.В., Сливкер В.И.** Расчетные модели сооружений и возможность их анализа. 4-е изд., перераб. и дополн-е. – М.: Изд-во СКАД СОФТ, 2017. – 736 с.
7. **Перельмутер А.В., Тур В.В.** Готовы ли мы перейти к нелинейному анализу при проектировании? // International Journal for Computational Civil and Structural Engineering, 2017. Vol. 13, No 3. – C. 86–102.
8. **Перельмутер А.В., Юрченко В.В.** Исследлвание области несущей способности тонкостенных стержневых элементов из холодногнутых профилей // Наука та будівництво, 2019, Том 21 № 3. – С. 42–48.
9. **Перельмутер М.А., Попок К.В., Скорук Л.Н.** Расчет ширины раскрытия нормальных трещин по СП 63.13330.2012 // Бетон и железобетон, 2014, № 1. – С. 21–22.
10. **Ясинский Ф.С.** Избранные работы по устойчивости сжатых стержней. – М.-Л.: Гостехиздат, 1952.

СП 63.13330.2018 Бетонные и железобетонные конструкции. Основные положения. СНиП 52-01-2003

СП 16.13330.2017 "Стальные конструкции. Актуализированная редакция СНиП II-23-81*"

Russian construction code SP 295.1325800.2017 Konstruktsii betonnyye, armirovannyye polimernoy kompozitnoy armaturoy. Pravila proyektirovaniya [Concrete structures reinforced with polymer composite reinforcement. Design rules]. Moscow: Standartinform, 2017. 48 p. (rus)

СП 14.13330.2018 Строительство в сейсмических районах. Актуализированная редакция СНиП II-7-81* Seismic building design code

СП 16.13330.2017 "Стальные конструкции. Актуализированная редакция СНиП II-23-81*" Steel structures

СП 63.13330.2018 Бетонные и железобетонные конструкции. Основные положения. СНиП 52-01-2003 Concrete and reinforced concrete structures. General provisions

СП 63.13330.2012 Бетонные и железобетонные конструкции. Основные положения. Актуализированная редакция СНиП 52-01-2003 Concrete and won concrete construction. Design requirements

Russian construction code SP 14.13330.2018 Stroitelstvo v sejsmicheskikh rajonakh [Seismic building design code] Moscow: Standartinform, 2018. 122 p. (rus)

Russian construction code SP 16.13330.2017 Stalnye konstrukcii [Steel structures] Moscow: Minstroii Rossii, 2017. 145 p. (rus)

Russian construction code SP 63.13330.2018 Betonnye i zhelezobetonnye konstrukcii. Osnovnye polozheniya [Concrete and reinforced concrete structures. General provisions] Moscow: Minstroii Rossii, 2018. 143 p. (rus).

Russian construction code SP 63.13330.2012 Betonnye i zhelezobetonnye konstrukcii. Osnovnye polozheniya [Concrete and won concrete construction. Design requirements] Aktualizirovannaya redakciya SNiP 52-01-2003.

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DURABILITY ASSESSMENT OF BENDING STRUCTURES MADE OF NONLINEAR ELASTIC MATERIAL

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Abstract: Experimental studies and field tests indicate that the effect of corrosive media leads to significant changes in the physical and mechanical characteristics of structural materials. The article proposes a mathematical model that allows predicting the negative impact of aggressive media and assessing the durability of bent structures.

Keywords: nonlinear elastic material, induced heterogeneity, aggressive environment, mathematical model, surface corrosion, durability

ОЦЕНКА ДОЛГОВЕЧНОСТИ ИЗГИБАЕМЫХ КОНСТРУКЦИЙ ИЗ НЕЛИНЕЙНО ДЕФОРМИРУЕМОГО МАТЕРИАЛА

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Аннотация: Экспериментальные исследования и натурные испытания свидетельствуют о том, что воздействие агрессивных сред приводит к существенным изменениям физико-механических характеристик материалов конструкций. В статье предложена математическая модель позволяющая прогнозировать отрицательное воздействие агрессивных сред и оценивать долговечность изгибаемых конструкций.

Ключевые слова: физическая нелинейность, наведенная неоднородность, агрессивная среда, математическая модель, поверхностная коррозия, долговечность

Currently, in the design of thin-walled structures, there is a tendency to take into account real operating conditions, which leads to the complication of the mathematical models describing these structures. When designing the evolution of the life cycle of building structures, it is necessary to digitize a number of parameters for monitoring objects during operation, one of which is the durability of structures as a whole and their elements. This will avoid an unpredictable loss of their bearing capacity and will protect against more serious consequences. Durability can be considered as the life of the object as a whole, and its individual structural elements, and also allows you to determine the timing of scheduled preventive and overhaul.

Structural elements in the process of work interact with different working environments, as a result of which, during their operation, the intensity and nature of the distribution of the existing "working" loads changes over time. The structures are periodically exposed to the influence of environments that are aggressive in relation to the materials used. As a result, the aggressive components of the external environment diffusing into the surface layers of the construction material break the internal connections and lead to a change in the physical and mechanical characteristics of the material. As a rule, this means a decrease in its strength and deformation characteristics. By an aggressive working environment, we mean one, the impact of which on the construction material leads to the degradation of its strength and deformation characteristics. By degradation we mean the process of deterioration of the physical and mechanical parameters of the material relative to their initial (initial) values.

During the operation of the structure, the concentration of aggressive substances from the external environment in the material of the structure can change, accelerating the degradation of strength characteristics and the accumulation of irreversible scattered damage. The conditional line that delimits the main material of the structure from the material affected by the aggressive environment will be called the degradation front. The advance of the degradation front into the material of the structure makes it inhomogeneous (induced inhomogeneity), in connection with which there is a redistribution of stresses and strains in it. As a result, a dangerous state of the structure arises, by which we mean the achievement of stresses at one of the points of the structure equal to the value of the strength criterion used. The time from the start of operation of the structure to the onset of a dangerous state will be called the durability of the structure.

The intensity of the impact of an aggressive environment depends on its concentration in the volume of the construction material. With an increase in concentration, a noticeable decrease in the temporary resistance of the material and an increase in the degree of nonlinearity of the deformation curve are observed. The model becomes more complicated and along with other characteristics a "slow" time parameter appears. Therefore, in order to create mathematical models describing the work of a construction material in an aggressive environment, it is necessary to carry out additional experimental research. The integral characteristic reflecting the change in material properties is the deformation curve. It most fully reflects the processes occurring in the material, when interacting with an aggressive working environment. By changing the deformation diagram, one can judge the ultimate strength and deformation properties of the material, its ability to harden or soften, the degree of aggressiveness of the external environment in relation to the material under consideration.

The presence of a large number of parameters that affect the processes of interaction between the material of the structure and the aggressive working environment leads to the fact that the creation of a general mathematical model that would take into account all possible manifestations of the aggressive effect of the environment on the material is extremely difficult, and this is not connected only with the complexity of the theoretical description, but also with certain problems in the formulation of experiments. Therefore, it is necessary to use a phenomenological approach and develop particular calculation models. This will allow building mathematical models on the basis of experimental data, without requiring complete clarity in the content of those physicochemical processes that occur during the interaction of material and an aggressive working environment.

When creating mathematical models, it is assumed that there are deformation curves obtained when testing specific materials that interacted with an aggressive medium for different times at different levels of preloading. In this case, on the basis of the experimental results, it is possible to construct the physical equations of the mechanics of a deformable solid, taking into account the above features.

In this article, a mathematical model is built that describes the interaction of a structure material with an aggressive working environment (surface corrosion). When creating a model, we will use the method of structural parameters, which consists in the fact that a function $F(z, t)$ is introduced into the physical equations of the mechanics of a deformable solid body that allows us to take into account the change in the strength and deformation characteristics of the material within the affected layer, which we call degradation. The degradation function $F(z, t)$ depends on the concentration of the aggressive environment. To construct the resolving relations, we take the theory of small elastic-plastic deformations by A.A. Ilyushin. The influence of an aggressive environment has been taken into account by introducing a scalar function $F(z, t)$ into the physical equations to describe the degradation of the secant module in the affected layer of the structural material. As a result, the stress deviator tensor is as follows:

$$D_\sigma = \frac{2}{3} F\left(z,t\right) E_c D_\varepsilon, \qquad (1)$$

where, D_σ – is stress deviator tensor, D_ε – is strain deviator tensor, $E_c = \sigma_i / \varepsilon_i$ – is secant module, σ_i – is stress intensity, ε_i – is strain intensity.

As a result of the interaction of the construction material with an aggressive environment, the physical and mechanical parameters in the affected layer of the material changes over time according to the laws that are determined by the results of experiments. To the physical equations, it is necessary to add kinetic equations, which are a mathematical model of the change in time of one or another parameter of the structure or the material from which it is made. They do not describe the physical and chemical processes causing these changes. Since this article considers a mathematical model of surface corrosion destruction, the general form of the kinetic equation looks like this:

$$\delta(t) = f(t). \qquad (2)$$

where $\delta(t)$ – is a depth of damaged layer, t – is a time.

The kinetic equations are based only on hypotheses and assumptions of a phenomenological nature and are a mathematical formalization of the experimental data obtained, therefore, they should be distinguished by mathematical simplicity. The kinetic equations cannot pretend to be very general, and are suitable only for obtaining a reasonable approximation when describing a limited class of phenomena [1].

The theory of beams, plates and shells, complicated by the developing inhomogeneity of the physical and mechanical properties of the material, leads to the need to solve nonlinear differential equations in partial derivatives, taking into account the history of deformation of the material and the degradation of its mechanical characteristics, and the development of effective algorithms for the numerical implementation of the obtained equations.

Let us consider the problem of interaction of a plate made of a nonlinearly deformable material with an aggressive environment and construct a mathematical model that allows us to determine its durability.

To construct the resolving equation for the bending of a plate from a physically nonlinear material, we write expression (1) in an incremental form [1]:

$$\frac{\Delta D_\sigma}{F} = \frac{2}{3}\left(E_k \Delta D_\varepsilon + E_c D_\varepsilon \frac{\Delta F}{F} \right), \qquad (3)$$

where ΔD_σ – is stress deviator tensor increment, ΔD_ε – is strain deviator tensor increment, E_k – is tangent module, ΔF – is degradation function increment. Expanding expression (3), we obtain an incremental system of physical equations in the following form [1]:

$$\begin{aligned}
\Delta\sigma_x &= -\frac{4}{3}E_k z\left(\frac{\partial^2 \Delta w}{\partial x^2} + \frac{1}{2}\frac{\partial^2 \Delta w}{\partial y^2}\right) - \frac{4}{3}E_c z\left(\frac{\partial^2 w}{\partial x^2} + \frac{1}{2}\frac{\partial^2 w}{\partial y^2}\right)\frac{\Delta F}{F},\\
\Delta\sigma_y &= -\frac{4}{3}E_k z\left(\frac{\partial^2 \Delta w}{\partial y^2} + \frac{1}{2}\frac{\partial^2 \Delta w}{\partial x^2}\right) - \frac{4}{3}E_c z\left(\frac{\partial^2 w}{\partial y^2} + \frac{1}{2}\frac{\partial^2 w}{\partial x^2}\right)\frac{\Delta F}{F},\\
\Delta\tau_{xy} &= -\frac{2}{3}E_k z\frac{\partial^2 \Delta w}{\partial x \partial y} - \frac{2}{3}E_c z\frac{\partial^2 w}{\partial x \partial y}\frac{\Delta F}{F},
\end{aligned} \qquad (4)$$

where Δw – is deflection increment, w – is accumulated deflection, $\Delta\sigma_x$, $\Delta\sigma_y$, $\Delta\tau_{xy}$ – is increments of stress tensor components.

When deriving the resolving equation for the plate bending, we assume that the plate deflections are small in comparison with the plate thickness and the Kirchhoff's hypothesis of direct normals is valid. Thus, the incremental bending equation of a plate made of a physically nonlinear material in an aggressive working environment will take the following form [1]:

$$\nabla^2\left(D_k\nabla^2\Delta w\right)-\frac{1}{2}L\left(D_k,\Delta w\right)=\Delta q-\Delta q_{\phi}^{*}. \qquad (5)$$

where $\Delta q(x,y)$ – is distributed load increment, Δq_{ϕ}^{*} – is "Fictitious" load, reflecting the influence of an aggressive environment on the plate material, D_k and D_c^* are variables in the spatial coordinates of the plate stiffness, which have the following form:

$$D_k=\frac{4}{3}\int\limits_{-0.5h}^{0.5h}E_k z^2dz,\quad D_c^*=\frac{4}{3}\int\limits_{-0.5h}^{0.5h}E_c z^2\frac{\Delta F}{F}dz. \qquad (6)$$

Differential operator $L(D_k, \Delta w)$ in the equation (5) has the form:

$$L\left(D_k,\Delta w\right)=\frac{\partial^2 D_k}{\partial x^2}\frac{\partial^2\Delta w}{\partial y^2}+\frac{\partial^2 D_k}{\partial y^2}\frac{\partial^2\Delta w}{\partial x^2}-2\frac{\partial^2 D_k}{\partial x\partial y}\frac{\partial^2\Delta w}{\partial x\partial y}. \qquad (7)$$

Expression for " fictitious " load Δq_{ϕ}^{*} in the equation (5) has the following form:

$$\Delta q_{\phi}^{*}=\nabla^2\left(D_c^*\nabla^2 w\right)-\frac{1}{2}L\left(D_c^*,w\right). \qquad (8)$$

When constructing a mathematical model of the interaction of a structure material with an aggressive working environment, the main task is to determine the type of degradation functions, the concentration of an aggressive environment and the kinetic equation. In order to obtain analytical expressions for the functions F and B, consider Fig. 1 [1, 3].

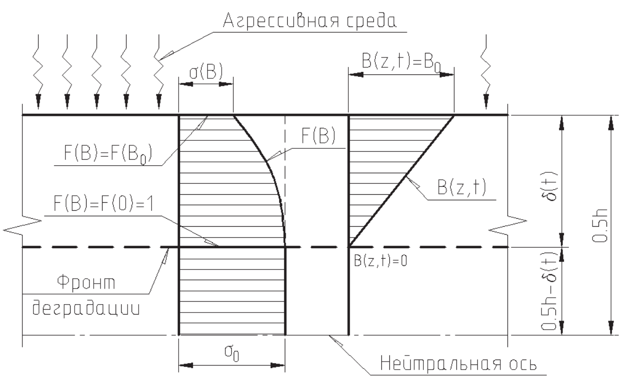

Figure 1. Interaction of the plate with an aggressive working environment

Based on experimental data and research results of other authors, let us assume that the degradation function has the form of an exponential [1, 2]:

$$F(B(z,t)) = \exp(-\lambda B(z,t)), \qquad (9)$$

where λ – parameter is experimental coefficient characterizing the degree of degradation of the deformation curve.

In general, to determine the concentration function of an aggressive medium, it is necessary to solve the mass transfer equation. Considering that, as a result of the interaction of the material of the structure and the aggressive working medium, the depth of penetration of the medium δ into the material of the structure is small compared to the thickness of the structure, it can be assumed that the change in the concentration of the aggressive medium occurs according to a linear law [1, 2]:

$$B(z,t) = a(t)z + b(t), \qquad (10)$$

where $a(t)$, $b(t)$ – are coefficients that are determined based on the conditions on the surface of the structure and on the boundary of the degradation front. We assume that on the surface of the structure at $z = 0.5h$, the concentration of the aggressive working medium $B(z,t) = B_0$ is considered constant throughout the entire interaction time, and the concentration of the medium at the boundary of the degradation front, that is, at $z = 0.5h - \delta$, is equal to zero $B(z,t) = 0$. Taking into account the above conditions, the function of concentration of an aggressive medium will take the following form:

$$B\left(z,t\right)=B_0\frac{2|z|+2\delta-h}{2\delta}\quad или\quad B\left(z,t\right)=B_0\frac{|z|-z_{\phi\partial}}{0.5h-z_{\phi\partial}} \qquad (11)$$

Using functions (9) and (11), we obtain the ratio $\Delta F/F$

$$\frac{\Delta F}{F}=-\lambda B_0\frac{h-2|z|}{2\delta^2}\Delta\delta \qquad (12)$$

Substituting (12) into the expression of variable stiffness D_c^* (6), after the necessary mathematical transformations, we obtain the expression for the "fictitious" load (8):

$$\Delta q^*_\phi = \frac{B_0 \lambda h}{2\delta^2} q(x, y)\Delta\delta. \qquad (13)$$

Let us give a method for determining the durability of a plate by the example of solving two problems. Consider two plates, square in plan, each of which is under the influence of a uniformly distributed load. The first plate is clamped along the entire contour, and the second has a hinge support along all edges. An aggressive medium is a 20% sodium hydroxide solution. The material of the plates is epoxy concrete [1, 2]. To solve the incremental differential equation (5), we use the Bubnov-Galerkin method. The depth of penetration of an aggressive medium (2) into the thickness of the material is calculated by the formula used by a number of authors:

$$\delta(t) = \alpha\sqrt{t}, \qquad (14)$$

where α – is experimental coefficient equal $13.05 \cdot 10^{-3}$ *м/год* (m/year).

The solution to equation (5) consists of two stages: at the first stage, a load Δq is sequentially applied to the plate until the initial load $q = \sum\Delta q$ is reached; at the second stage, we take the increment in the thickness of the damaged layer $\Delta\delta$ as the leading parameter, with $\delta = \sum\Delta\delta$. To implement the algorithm of the sequential loading method, the load is divided into 256 layers. The penetration of an aggressive medium into the thickness of the structure material is taken into account by the successive displacement of the degradation front into the plate material by the value $\Delta\delta = h/256$. Below in Fig. Figures 2 and 3 show the results of determining the durability of a plate rigidly clamped along the entire contour (Fig. 2) and a plate simply supported along the entire contour (Fig. 3).

In fig. 2 and 3 the following designations are used: 1 – long-term strength curve; 2, 3, 4 – curves of the highest stress intensity in the plate $\sigma_{i,\max}$ at different levels of loading with a distributed load. For curves 2, 3 and 4, the aggressive environment began to act at loads equal to 80%, 50%, and 30% of the ultimate load. The above calculation results allow us to determine the time of the onset of a dangerous state in the T plates. A dangerous state is the point of intersection of the ascending curve 1 with curves 2, 3 and 4. In fig. 2 – T_1 = 0.39, T_2 = 1.75 and T_3 = 3.22. In fig. 3 – T_1 = 0.43, T_2 = 1.72 and T_3 = 3.11. It can be concluded that the boundary conditions insignificantly affect the longevity of the plate.

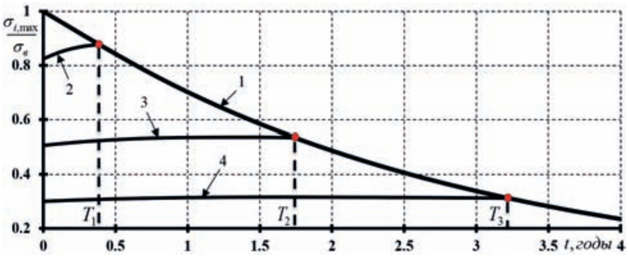

Figure 2. Determination of the durability of the plate rigidly clamped along the entire contour

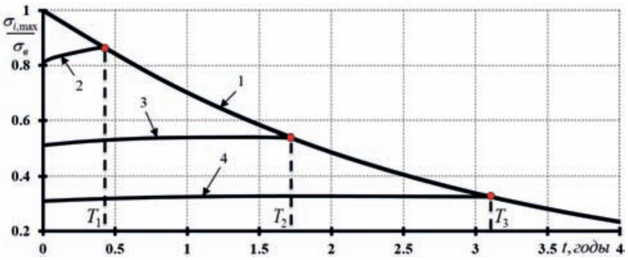

Figure 3. Determination of the longevity of the plate simply supported along the entire contour

REFERENCES

1. **Petrov V.V.** Nelinejnaya inkremental'naya stroitel'naya mekhanika [Nonlinear Incremental Structural Mechanics]. Moscow, Infra-Inzheneriya, 2014, 480 pages (in Russian).
2. **Petrov V.V., Ovchinnikov I.G., Shihov Yu.M.** Raschet elementov konstrukcij, vzaimodejstvuyushchih s agressivnoj sredoj [Structural Analysis with Allowance for Aggressive Media]. Saratov, Izdatelstvo Saratovskogo universiteta, 1987, 288 pages (in Russian).
3. **Petrov V.V., Mishchenko R.V.** Ob odnoj modeli dolgovechnosti izgibaemyh konstrukcij [About one model of Long-Term Durability of Construction Materials, Products and Structures]. // Dolgovechnost' stroitel'nyh materialov, izdelij i konstrukcij: materialy

Vseros. nauch.-tekhn. konf., posvyashch. 75-letiyu zasl. deyatelya nauki RF, akad. RAASN, d-ra tekhn. nauk, prof. Selyaeva V.P. (3-5 dek. 2019 g.). Saransk: Izd-vo Mordov. un-ta, 2019, pp. 250–257 (in Russian).

СПИСОК ЛИТЕРАТУРЫ

1. **Петров В.В.** Нелинейная инкрементальная строительная механика. – М.: Инфра-Инженерия, 2014. – 480 с.
2. **Петров В.В., Овчинников И.Г., Шихов Ю.М.** Расчет элементов конструкций, взаимодействующих с агрессивной средой. – Саратов: Издательство Саратовского университета, 1987. – 288 с.
3. **Петров В.В., Мищенко Р.В.** Об одной модели долговечности изгибаемых конструкций. // Долговечность строительных материалов, изделий и конструкций: материалы Всерос. науч.-техн. конф., посвящ. 75-летию засл. деятеля науки РФ, акад. РААСН, д-ра техн. наук, проф. Селяева В.П. (3–5 декабря 2019 года). – Саранск: Издательство Мордовского университета, 2019, с. 250–257.

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COMPUTER SIMULATION OF STRUCTURAL VIBRATION DAMPING WITH ALLOWANCE FOR NONLOCAL PROPERTIES

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Abstract: Different approaches to the computer simulation of damping properties of structural elements, which are made of materials with complicated physical structure, such as composites and nano-materials, are considered in this paper. In such cases application of classical models, e.g. ones based on the Kelvin-Voight hypothesis, can lead to the results that are not even close to the real composite structure behavior. The main point of the proposed approaches is delocalization of the damping effects in space and time. The described nonlocal damping models are more flexible in comparison to classic ones. The model calibration based on the experiment data allows to determine the optimum value of the characteristic parameter of nonlocal model using the least square method. The results of three-dimensional numerical simulation of the composite beam vibration were used for model calibration. The numerical simulation was implemented in SIMULIA Abaqus software. The material was considered as orthotropic; its parameters were picked up according to the physical properties of the real composite material. The developed beam vibration models considering nonlocal damping were created in MATLAB. The obtained results were compared to the results based on classic Kelvin-Voight damping model.

Keywords: structural vibration, nonlocal damping, numerical simulation, flexible model

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ГАШЕНИЯ КОЛЕБАНИЙ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ С УЧЁТОМ НЕЛОКАЛЬНОСТИ ИХ ДЕМПФИРУЮЩИХ СВОЙСТВ

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Аннотация: Рассматриваются подходы к численному моделированию демпфирующих параметров конструкций, выполненных из материалов со сложной физической структурой, таких как композитные и нано-материалы. Использование в этом случае классических моделей демпфирования, к примеру, основанных на гипотезе вязкого трения Фойгта, приводит к результатам расчёта, весьма далеким от реального поведения конструкций из подобных материалов. Предлагаемые в статье подходы заключаются в делокализации эффекта демпфирования, как по пространственной координате, так и во времени. Описываемые нелокальные модели демпфирования являются управляемыми. Калибровка моделей по результатам эксперимента заключается в выявлении оптимального значения управляемого параметра модели с использованием метода наименьших квадратов. В качестве опорных результатов в статье использованы данные вычислительного эксперимента над трёхмерной моделью стержневого элемента, выполненного из композитного материала. Этот численный эксперимент проведен с использованием программного комплекса SIMULIA Abaqus. Материал при этом представлен ортотропным, параметры ортотропии назначались в соответствии с физическими характеристиками рассматриваемого композитного материала. Разработанные вычислительные модели колебаний стержневого элемента с учётом нелокальности демпфирования были реализованы в программном комплексе MATLAB. Приведено сравнение полученных результатов с результатами расчётов, полученных с использованием классической модели демпфирования, основанной на гипотезе Фойгта.

Ключевые слова: колебания конструкций, нелокальное демпфирование, вычислительный эксперимент, управляемая модель

INTRODUCTION

The materials with complicated physical structure, such as composite materials and nano-materials, become more and more widespread in the engineering practice. Generally, for the design of structures, made of such materials, the detailed three-dimensional finite element models are used. In such models materials generally are modeled as orthotropic and anisotropic ones. Problem of damping modeling for the structural composite elements is especially sophisticated. Meanwhile, the detailed three-dimensional modeling of, for example, beam elements is very often cumbrous and unreasonable. In this case, one-dimensional models, which are flexible enough for damping simulation for the composite structures, are preferable. Nonlocal damping model can be used as such flexible model.

VIBRATION SIMULATION USING NONLOCAL IN SPACE DAMPING MODEL

Damping in the certain point of the structure with longitudinal coordinate $x1$ is assumed to be dependent not only on local value of motion velocity at this point $v(x1)$, but also on the values of motion velocity in the neighboring points. The more distance between the two points the lower influence that one of them has on the other [2].
The Kelvin-Voigt material model is commonly used to describe the damping process in engineering structures:

$$\sigma = E\varepsilon + \gamma E\dot{\varepsilon}\,, \tag{1}$$

where σ, ε – normal stress and axial strain, $\dot{\varepsilon}$ – strain rate, E – Young modulus, γ – damping ratio. If we consider damping nonlocal in space, then equation (1) transforms to [2]:

$$\sigma(x,t) = E[\varepsilon(x,t) + \gamma\int_0^l C_v(|x-\theta|)\dot{\varepsilon}(\theta,t)d\theta]. \tag{2}$$

Here $C_v(|x-\theta|)$ – the kernel function of internal damping, $|x-\theta|$ – distance between the neighboring points. The $C_v(|x-\theta|)$ function must satisfy to normalization requirement:

$$\int_{-\infty}^{\infty} C_v(|x-\theta|)d\theta = 1. \tag{3}$$

In the paper the error kernel function is used:

$$C_v(|x-\theta|) = \frac{\mu}{\sqrt{2\pi}}\cdot e^{\frac{-\mu^2(x-\theta)^2}{2}}. \tag{4}$$

Here μ is the parameter that characterizes the space nonlocality level in the damping model (fig. 1). The higher is μ, the closer is the damping model to the classic local one (1).

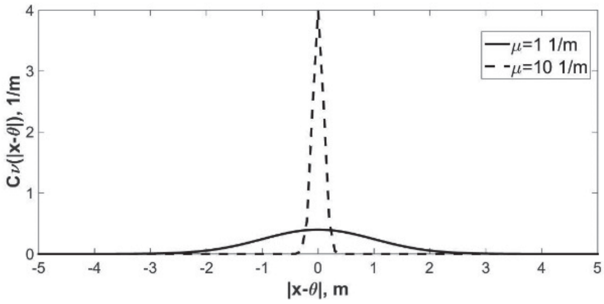

Figure 1. Error kernel functions for different influence distance parameter

The equilibrium equation for the Euler-Bernoulli beam is:

$$\frac{\partial^2 M(x,t)}{\partial x^2} = m\frac{\partial^2 v(x,t)}{\partial t^2} - q(x,t). \tag{5}$$

Here $v(x,t)$ is beam deflection, m is the distributed mass, $q(x,t)$ – distributed load.
Considering (2) and the plane sections assumption, the bending moment expression for the nonlocal approach is:

$$M(x,t) = -EI\left[\frac{\partial^2 w(x,t)}{\partial x^2} + \gamma\int_0^l C_v(|x-\theta|)\frac{\partial^3 w(\theta,t)}{\partial\theta^2\partial t}d\theta\right], \tag{6}$$

where EI – the bending stiffness of the beam.
Substituting the second derivative of the bending moment expression (6) to the left part of the equation (5), we obtain the vibrating beam

equilibrium equation regarding the deflection function $v(x,t)$:

$$\frac{\partial^2 v(x,t)}{\partial t^2}+\frac{EI}{m}\left[\frac{\partial^4 v(x,t)}{\partial x^4}+\right.$$
$$\left.+\gamma\frac{\partial^2}{\partial x^2}\int_0^l \mathrm{C_v}(|\mathrm{x}-\theta|)\frac{\partial^3 v(\theta,t)}{\partial\theta^2\partial t}d\theta\right]=\frac{q(x,t)}{m}. \tag{7}$$

To solve the equation (7) Galerkin method was used, with the first beam Eigen forms, responding to the boundary conditions, considered as the coordinate functions. The satisfying number of the coordinate functions was picked up based on the numerical study of the results convergence.

Consider GFRP beam with the fixed ends made of orthotropic thermoset vinyl ester class 1 FRP under instantly applied distributed load q = 10 *kN/m*. The beam is 6 m long and has a rectangular cross-section. The characteristics of the material obtained experimentally in [9, 10, 11].

The method of determining the influence distance μ using the least squares based on the numerical simulation data is described in [6]. This method was also used in this paper. For the nonlocal in space damping model calibration the three-dimensional finite element model of the beam was constructed in SIMULIA Abaqus CAE (fig .2).

The material is suggested to be orthotropic. The calibrated value of the influence distance is μ = 1.071/*m* Comparison between the results of one-dimensional modelling of the beam vibrations considering nonlocal in space damping with

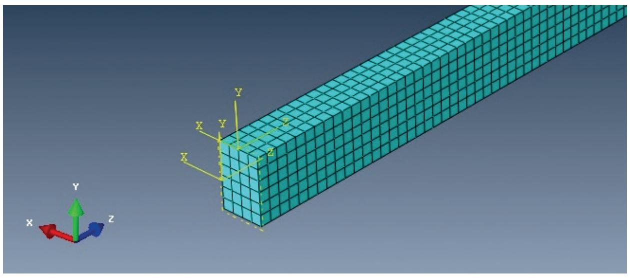

Figure 2. Finite element model of the considering beam in SIMULIA Abaqus CAE

the calibrated μ and the results of detailed three-dimensional finite element simulation is shown on the fig. 3.

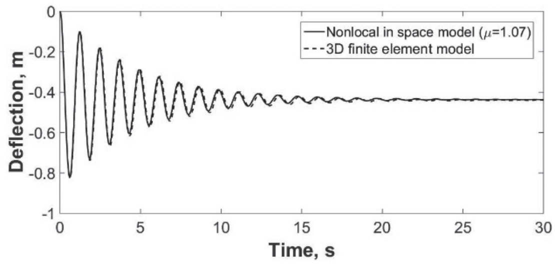

Figure 3. Comparison of the results obtained using nonlocal in space damping model and ones obtained in Abaqus CAE

The difference between Abaqus results obtained with 3D orthotropic material model and the results obtained with one-dimensional beam where local Kelvin-Voigt model is used to describe damping is shown on fig. 4.

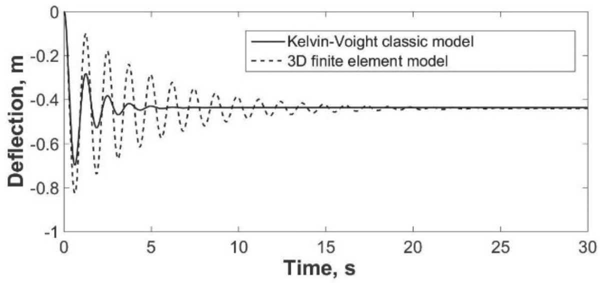

Figure 4. Deflection of the beam using local Kelvin-Voigt damping model in comparison to 3D numerical simulation data

VIBRATION SIMULATION USING NONLOCAL IN TIME DAMPING MODEL

The beam element vibration process considering damping that is nonlocal in time is modeled using the finite element analysis. Using this method, the equilibrium equation of the beam bending in time is solved. In FEA the equilibrium equation is applied in matrix form:

$$M \cdot \ddot{\bar{V}}(t) + D \cdot \dot{\bar{V}}(t) + K \cdot \bar{V}(t) = \bar{F}(t). \tag{8}$$

Here $\acute{V}(t)$ – vector of displacements of the finite element model nodes (dot indicates time derivative), K – stiffness matrix of the finite element model, D – damping matrix, M – mass matrix, $\acute{F}(t)$ – vector external forces that are acting at the considered point of the structure.

To simulate the nonlocal in time properties of structural vibration damping («damping with memory») equation (8) is represented as:

$$M \cdot \ddot{\bar{V}}(t) + D \cdot \int_0^t G(t-\tau) \cdot \dot{\bar{V}}(\tau) d\tau + K \cdot \bar{V}(t) = \bar{F}(t). \tag{9}$$

Here $G(t-\tau)$ is the kernel function for nonlocal in time damping. This function describes the decrease of the strain rate influence at the moment τ on the damping at the current moment t, and:

$$\int_0^t G(t-\tau) d\tau = 1. \tag{10}$$

As above, the error function is taken here for error function, constructed on the base of Gauss integral:

$$\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}, \tag{11}$$

that, taking into account the condition (10), can be written as:

$$G(t-\tau) = \frac{2\mu}{\sqrt{\pi}} \cdot e^{-\mu^2 (t-\tau)^2}, \tag{12}$$

Here μ is a parameter, that characterize the level of damping nonlocality in time.

To solve the dynamic equilibrium equation, the method of the central differences is used [8]. In this case, the first and second order time derivatives of the displacement vector $\acute{V}(t)$ participating in (8) and (9) are approximated by central finite differences. Then the equation (8), obviously, takes the following form:

$$\frac{1}{\Delta t^2} \cdot M \cdot (\bar{V}_{i+1} - 2\bar{V}_i + \bar{V}_{i-1}) + \frac{1}{2 \cdot \Delta t} \cdot D \cdot (\bar{V}_{i+1} - \bar{V}_{i-1}) + K \cdot \bar{V}(t) = \bar{F}_i. \tag{13}$$

Here $i = 1, 2, 3, \ldots$ – number of the considered moment in time t, Δt – time increment.

In order to replace the classical damping model in (13) with the damping model with memory, at first we represent the central difference in the second term on the left-hand side of equation (13), which is responsible for damping, as the average of the «forward» and «backward» differences:

$$\frac{1}{\Delta t^2} \cdot M \cdot (\bar{V}_{i+1} - 2\bar{V}_i + \bar{V}_{i-1}) + \frac{1}{2 \cdot \Delta t} \cdot D \cdot (\bar{V}_i - \bar{V}_{i-1}) + \frac{1}{2 \cdot \Delta t} \cdot D \cdot (\bar{V}_{i+1} - \bar{V}_i) + K \cdot \bar{V}(t) = \bar{F}_i. \tag{14}$$

The term with the «backward» difference is replaced by:

$$\frac{1}{2 \cdot \Delta t} \cdot D \cdot (\bar{V}_i - \bar{V}_{i-1}) = \frac{D}{2} \sum_{j=1}^{i} \bar{G}(i,j) \left(\bar{V}_j - \bar{V}_{j-1}\right), \tag{15}$$

where i – number of the time step which is corresponding to the considered time moment t, $t = \Delta t \cdot i$, $\tau = \Delta t \cdot j$, $j = 1, 2, \ldots, i$ – number of the time step when calculating the kernel $\acute{G}(i, j)$. $\acute{G}(i, j)$ is the discrete analogue of $G(t-\tau)$ kernel (12), which for the error function (12) is calculated as follows:

$$\bar{G}(i,j) = \frac{2\mu}{\sqrt{\pi}} \cdot e^{-\mu^2 \left(t - \left(\tau - \frac{\Delta t}{2}\right)\right)^2}. \tag{16}$$

After the described transformations equation (14) can be written as:

$$\frac{1}{\Delta t^2} \cdot M \cdot (\bar{V}_{i+1} - 2\bar{V}_i + \bar{V}_{i-1}) + \frac{D}{2} \cdot \bar{Z} + \frac{1}{2 \cdot \Delta t} \cdot D \cdot (\bar{V}_{i+1} - \bar{V}_i) + K \cdot \bar{V}(t) = \bar{F}_i, \tag{17}$$

where

$$\bar{Z} = \frac{2\mu}{\sqrt{\pi}} \cdot e^{-\mu^2 \left(t - \left(\tau - \frac{\Delta t}{2}\right)\right)^2} (\bar{V}_i - \bar{V}_{i-1}). \tag{18}$$

Still, the influence distance μ determine the nonlocality level in structure. The higher is μ, the closer is the damping model to the classic one.

Transform (17) to the computational scheme for the step-by-step calculating of $\acute{V}_{i+1}$ using the vectors $\acute{V}_i$ and $\acute{V}_{i-1}$, which are calculated on the increments i and $i-1$:

$$\bar{V}_{i+1} = Q \cdot \bar{F}_i - Q_1 \cdot \bar{V}_i - Q_2 \cdot \bar{V}_{i-1} - Q_3 \cdot \bar{Z}, \tag{19}$$

where:

$$Q = \left(\frac{1}{\Delta t^2}M + \frac{1}{2 \cdot \Delta t}D\right)^{-1},$$
$$Q_1 = Q \cdot \left(-\frac{2}{\Delta t^2}M - \frac{1}{2 \cdot \Delta t}D + K\right),$$
$$Q_2 = \frac{1}{\Delta t^2}Q \cdot M, \tag{20}$$
$$Q_3 = \frac{1}{2}Q \cdot D.$$

For the first step $i = 1$ we assume $\acute{V}_0 = 0$ and $\acute{V}_1 = 0$ as the initial conditions.

The calibration of the nonlocal in time damping model was implemented, as above, based on the results of the numerical simulation of three-dimensional finite element beam vibration in SIMULIA Abaqus CAE. The determined optimum value of μ for the beam, that was considered in privious section, is $\mu = 0.11/s$. The displacements of middle section of the beam in time are shown in fig. 5. The solid line shows the displacements of the beam which is obtained using a calibrated nonlocal model, and the dashed curve – using a 3D model built in SIMULIA Abaqus.

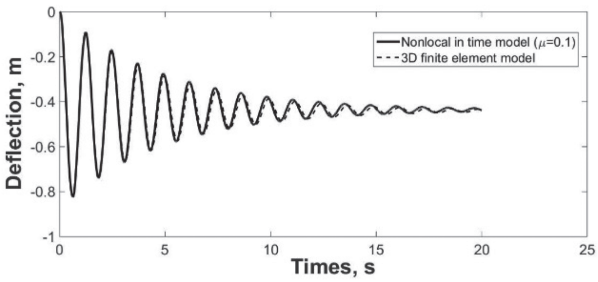

Figure 5. Deflection of the beam obtained with calibrated nonlocal in time damping model in comparison to 3D numerical simulation data

It is obvious, that calibrated nonlocal model allows to obtain much more accurate results, than the Kelvin-Voight classic model (fig. 4).

CONCLUSION

In comparison to local time models the model presented in this article allows managing the main characteristics of the simulated composite structures vibration process in more reliable and flexible way. Increased flexibility makes it possible to use one-dimensional models of beam elements in the dynamic analysis of structures which are made of modern composite materials with orthotropic properties.

REFERENCES

1. **Banks H.T. and Inman D.J.** 1991 On damping Mechanisms in Beams Journal of Applied Mechanics, 58(3). – pp. 716–723.
2. **Lei Y., Friswell M.I. and Adhikari S.** 2006 A Galerkin Method for Distributed Systems with Non-local Damping Int.Journal of Solids and Structures 43. – p. 3381–3400.
3. **Rossikhin Yu.A. and Shitikova M.V.** 2010 Application of Fractional Calculus for Dynamic Problems of Solid Mechanics: Novel Trends and Recent Results Applied Mechanics Reviews 63 010801 p. 1–52.
4. **Potapov V.D.** 2012 Problems of Machinery and Reliability p. 25–31.
5. **Fyodorov V.S., Sidorov V.N. and Shepitko E.S.** 2018 Nonlocal damping consideration for the computer modelling of linear and nonlinear systems vibrations under the stochastic loads IOP Conf. Series: Materials Science and Engineering 456 012040
6. **E.S. Shepitko and V.N. Sidorov**. Defining of nonlocal damping model parameters based on composite beam dynamic behaviour numerical simulation results // IOP Conf. Series: Materials Science and Engineering 675 (2019) 012056
7. **Akimov P.A., Belostosky A.M., Kaytukov T.B., Mozgaleva M.A. and Aslami M.** 2018 About Several Numerical and Semianalytical Methods of Local Structural Analysis Int. Journal for Computational Civil and Structural Engineering 14 i 4 p. 59–69.
8. **Bathe K.-J., Wilson E.L**. Chislennye metody analiza i metod konechnyh jelementov [Numerical methods in finite element analysis]. Moscow, Stroyizdat, 1982 (in Russian).
9. **Landherr J.C.** Dynamic analysis of a FRP deployable box beam. Master of Applied Science Thesis. Kingston: Queen's University, 2008.

10. **Lim R.A.** 2016 Structural monitoring of a 10m fibre reinforced polymer bridge subjected to severe damage (Kingston: Queen's University)
11. **Xie A.** Development of an FRP Deployable Bridge, Master of Applied Science Thesis, Department of Civil Engineering, Royal Military College of Canada, 2007.

СПИСОК ЛИТЕРАТУРЫ

1. **Banks H.T. and Inman D.J.** 1991 On damping Mechanisms in Beams Journal of Applied Mechanics, 58(3). – pp. 716–723.
2. **Lei Y., Friswell M.I. and Adhikari S.** 2006 A Galerkin Method for Distributed Systems with Non-local Damping Int.Journal of Solids and Structures 43. – p. 3381–3400.
3. **Rossikhin Yu.A. and Shitikova M.V.** 2010 Application of Fractional Calculus for Dynamic Problems of Solid Mechanics: Novel Trends and Recent Results Applied Mechanics Reviews 63 010801 p. 1–52.
4. **Potapov V.D.** 2012 Problems of Machinery and Reliability p. 25–31.
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7. **Akimov P.A., Belostosky A.M., Kaytukov T.B., Mozgaleva M.A. and Aslami M.** 2018 About Several Numerical and Semianalytical Methods of Local Structural Analysis Int. Journal for Computational Civil and Structural Engineering 14 i 4 p. 59–69.
8. **Бате К.-Ю., Вилсон Э.Л.** Численные методы анализа и метод конечных элементов. М., Стройиздат, 1982.
9. **Landherr J.C.** Dynamic analysis of a FRP deployable box beam. Master of Applied Science Thesis. Kingston: Queen's University, 2008.
10. **Lim R.A.** 2016 Structural monitoring of a 10m fibre reinforced polymer bridge subjected to severe damage (Kingston: Queen's University)
11. **Xie A.** Development of an FRP Deployable Bridge, Master of Applied Science Thesis, Department of Civil Engineering, Royal Military College of Canada, 2007.

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PROSPECTS FOR THE DEVELOPMENT OF THE REGULATORY FRAMEWORK OF INFORMATION SYSTEMS FOR "GREEN" STANDARDIZATION

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Abstract: Standards of the profile "Methods and means of creating, maintaining and developing Informatization", the main principles and directions of "green" standardization are developed. These provisions include: the main directions for creating a regulatory framework for Informatization of green standardization and the main directions for creating regulatory support for information technologies of "green" standardization, which determine the directions of work in creating an information environment for "green" standardization.

Keywords: environmental technology, information technology, artificial intelligence, environmental safety, "green" standards, "green" innovative technology, "green" innovative products

ПЕРСПЕКТИВЫ РАЗВИТИЯ НОРМАТИВНОЙ БАЗЫ ИНФОРМАЦИОННЫХ СИСТЕМ "ЗЕЛЕНОЙ" СТАНДАРТИЗАЦИИ

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Аннотация. В статье представлены основные положения и направления развития нормативно-правовой базы информатизации "зеленой" стандартизации. Основной профиль стандартов зеленого направления выделен по базовой тематике: – методы и средства создания, сопровождения и развития информатизации зеленой стандартизации. По приведенному анализу стандартов профиля "Методы и средства создания, сопровождения и развития информатизации" разработаны основные принципы и направления зеленой стандартизации. К этим положениям относятся: главные направления создания нормативно-правовой базы информатизации зеленой стандартизации и главные направления создания нормативно-правового обеспечения информационных технологий зеленой стандартизации, которые определяют направления работ при создании информационной среды зеленой стандартизации.

Ключевые слова: технология среды жизнедеятельности, информационная технология, искусственный интеллект, экологическая безопасность, "зеленые" стандарты, "зеленая" инновационная технология, "зеленая" инновационная продукция

INTRODUCTION

Principles and directions of development of the regulatory framework for Informatization of "green" standardization. First, we need to answer the question: how can green standards for innovative products and innovative technologies be expressed in a clear form for artificial intelligence (AI)? Before answering this technical question, it is appropriate to answer the ideological question: what does artificial intelligence have to do with it? Why convert green standards into computer programs? The answer is simple: recently, it has become possible and cost-effective to solve problems of improving the living environment and public health with the help of artificial intelligence

[1], [2], [3]. Modern information technologies (it) are characterized by the use of artificial intelligence methods in software. Currently, the process of "intellectualization of information technologies" is the main one. We are referring to the following trend: in the beginning, it performed the function of "big compute", and now it processes the knowledge presented in databases. Over the past 50 years, the total computing power of computers has grown more than 10^{10} times! [4], [5]. Recently, the results of AI application have gone beyond academic developments and are used in practical applications of environmental impact assessment (OS) of construction and other technologies [6], [7]. Artificial intelligence systems are usefully used in real life, from environmental diagnostics of the territories where objects are located to the management of construction robots and construction industry devices [8].

The report of the National intelligence Council of the United States (2017) from the series " Global trends "with the subtitle" Paradox of progress " [9], based on a survey of more than 2,500 experts from 35 countries, contains several alternative scenarios for the future. The Preface to the report emphasizes that the report does not claim to be final forecasts, but only a Preface to the discussion of the near future.

High risks require active cooperation of all countries of the world, involving the potential of artificial intelligence to prevent possible attacks of environmental terrorism and dangerous climate change.

Experts of the National intelligence Council of the United States note that the current situation is full of paradoxes: the progress of recent decades has contributed to the empowerment of a large number of people, but this same progress has generated the global financial crisis of 2008 and the growth of political populism in many countries of the world. They are confident that in the next five years, tensions will increase both within individual countries and in relations between countries. Competition at the international level will increase, and it will become increasingly difficult for countries to work together to solve common problems. The reasons for the crisis of cooperation will be differences on issues of environmental safety, religion, and individual rights. Differences in values and interests between States will threaten international security [10].

The way out of the problematic global situation can be the artificial intelligence of the United Nations, which is not burdened with the feelings of living people, and which can find cardinal solutions without emotions, first of all on the problem of environmental safety of the planet based on green standards. We need a new regulatory climate, without which it is impossible to use green innovative technologies. Outdated standards are not adapted to solve the described problems [11].

The main feature of the development of the regulatory framework in the field of Informatization of green standardization at the new stage is the deep penetration of modern computer equipment and computer technologies in all areas of activity, including the educational process and the transfer of green standards and innovations in the industry.

The legal framework for Informatization in the field of green standardization should establish the legal basis for the functioning of the information system at all stages of its development and implementation [12].

From the point of view of regulatory support, the green standardization information system is divided into two interrelated and complementary parts:

– legislative, including international, national and industry standards, as well as a set of legislative documents that define the basic principles of management in the field of industries (Rosatom, Rosstroy, etc.);

– regulatory and legal, including instructions, orders and orders, plans, norms, standards, etc., defining the mode, conditions and rules of operation of facilities and service personnel of industries (Rosatom, Rosstroy, etc.)

If the first set of documents defines the regulatory framework for creating and operating the information environment of green standardization, the second is the regulatory framework for implementing the transfer of innovative developments of the green environment, green products and green technologies created in the educational environment through graduates sent to the relevant industries, in the practice of urban planning.

As a result of rapid development of social information networks innovation in the world has increased dramatically, there electroremote Autonomous cars appeared building robots and building robotic systems, there are software platforms that exist all of today's software applications and the smartphones gained rapid development, there are many other gadgets [13].

The accelerated development of it is increasing with the approach of the singularity era, when It will become an intermediary in all technologies and spheres of human activity. The educational sphere, including in the field of construction, should be rebuilt in a timely manner so that the University would adapt to the new conditions in advance, that is, it could be a locomotive for the development of AI, that is, corresponding to the green standards of the new natural environment of life. For example, today, thanks to the innovative achievements of digitalization, all financial organizations are concerned about their fate due to the emergence of digital blockchain technologies and cryptocurrencies such as bitcoin, and all transport companies are involved in the development of driverless cars after Tesla started this trend. Educational services may change unrecognizably in the near future in comparison with traditional processes in education [14], [15].

To achieve the goals of green standardization in the educational environment, it is necessary to create a unified automated system for processing information (information) about standards and regulatory documents based on modern computer technology and on the basis of widespread introduction of the latest methods of processing information materials and improving methods of analysis and synthesis of information.

With the development of an automated processing system, documentation must be provided for compatibility of all its systems. Such compatibility can be provided by the common organizational structure, the unity of the information search language, the combination of technical means, the unity of software, a single procedure for collecting and processing information, the unification of documentation and information encoding [15].

Direct leadership and involvement of interested Departments, offices and divisions should be a prerequisite for effective and timely development of the regulatory framework.

1. FORMULATIONS OF THE PROBLEM

Basic principles of Informatization of "green" standardization. The main principle of work on green standardization in the field of Informatization should be the formation and implementation of a unified methodological approach to the creation, maintenance and development of information technologies in the educational environment and in industrial sectors.

The main goal of Informatization and standardization is to reduce the complexity, cost, and time required to create information technologies in industry and education, as well as to ensure their compatibility, portability, quality, and safety of operation.

Each specific project to create information technologies for green standardization should have a regulatory framework that covers all the required objects of standardization. The status of regulatory documents in this database may be different for different objects of green standardization: international standards, national standards of Russia, industry standards and guidelines, standards of enterprises and organizations for which green standardization information technologies are created.

The main stages and work on the design of information technologies are reflected in a set of international and national standards, as well as "de facto"standards. However, the existing standards do not disclose and regulate everything, but the most simple and traditional, available work unification. In addition, it should be borne in mind that during the development and approval of any ISO standard (usually about 5 years), there are such significant changes in modern methods and tools for creating information technologies that they cannot be tracked in the "de jure"standards. The most advanced "de facto" standards become the basis for the next generation of ISO standards. In this regard, to regulate the methods and processes of creating, maintaining and developing information technologies for green standardization, it is necessary to create industry-specific guidelines and regulatory documents, taking into account all existing features [15].

Effective application of a set of industry-specific regulatory and technical documents should be supported by a comprehensive system of interrelated tools for automating the creation, maintenance and development of software for modern information technologies for green standardization. When choosing tools for automating certain types of work, it is necessary to provide for the possibility of their joint functioning and interaction with a single repository of project data, as well as to create a set of working methods for the use of tools that take into account the provisions of regulatory, technical and methodological documents.

The objects of standardization listed in this section, existing international and national standards, as well as "de facto" standards should be used as input data when forming the regulatory framework for each project.

The application of the principles of functional standardization in the creation, maintenance and development of information technologies for green standardization allows you to develop and include in the documentation of each specific system a set of standards that define solutions for the architecture and structure of the system, as well as regulated rules for performing work throughout its life cycle [15].

2. ACCEPTED PRINCIPLES AND METHODS

The principle of building and applying profiles of automation objects of "green" standardization.

The definition of "profile" according to GOST R ISO/IEC TO 10000-1-99 as a subset of mandatory and optional features, requirements and parameters of one or a set of basic standards selected for inclusion in the profile is very strict. In this sense, profiles are used to specify the architecture and structure of automated systems of all types that are part of the automated green standardization management system.

When considering the regulatory framework governing the development, operation, maintenance and development of an information system for "green" standardization, the following standard profiles should be highlighted:

- methods and tools for creating, maintaining and developing green standardization information systems;
- software tools in the client-server architecture;
- user interfaces as an architectural component of the computing environment;
- telecommunication environment;
- information security methods and tools;
- legal issues of creating software tools.

Building and applying profiles requires a clear construction of basic standards that specify objects such as function sets, interfaces, and interaction protocols.

In addition, you may need to add specific processes, activities, and tasks related to the specifics of automated systems and their components to the selected subset of lifecycle processes. A number of works, especially at the most creative stages of software development, are not regulated by the standards. This does not allow you to develop and apply life cycle profiles for automated systems, as well as a number of other profiles based only on standards. It is advisable to additionally regulate such work with industry-specific regulatory and technical documents or enterprise standards.

The main obstacle to the creation of a regulatory framework in the field of green education that regulates the development, operation, maintenance and development of an information system for green standardization is the lack of a program and work plan in this area. And the lack of an up-to-date automated database of international and national standards in the field of Informatization and standardization makes such developments imperfect.

The list in the field of Informatization considered in this paper, consisting of more than 500 names of current international and national standards, as well as their analysis, is the basis of the article.

Life cycle of green innovative products

In General, the life cycle of green innovation products, consisting of the life cycles of the components, can be illustrated as follows.

CALS technologies are information support technologies for the life cycle of green innovative products.

The object of CALS-technologies is including information relating to impacts on the environment during the lifecycle of the product, impacts the production environment and impacts of manufacturing technology, impacts of logistics, impacts sales impacts operation impacts maintenance and repair of the product, and the technology is understood as a continuous information support of life cycle, meaning that every moment of life cycle data on environmental impacts from products authorized to share it with stakeholders.

Currently, CALS is understood as Continuous Acquisition and Life Cycle Support – continuous information support for the product or product lifecycle. At its core, today CALS is a global strategy for improving the efficiency and environmental safety of business processes performed during the product lifecycle through information integration and continuity of information generated at all stages of the life cycle. The means of implementing this strategy are CALS technologies, which are based on a set of integrated information models – the life cycle itself and the business processes performed during it, the product (product), the production and operational environment, and so on. The possibility of sharing information is provided by the use of computer networks and standardization of data formats, which ensures their correct interpretation.

BIM design and green construction of facilities

BIM technology is the organization of flows of project-building and project-technological information [5]. There are almost no environmental impacts at the planning and design stage of green products. The impact on the environment appear at the moment of the beginning of the project. In the UK, there is a standard BS1192 "Joint production of architectural, engineering and design information" (BS1192: 2007). The standard allows you to quickly systematize the requirements for design documentation and automate the verification of their implementation. If the project does not meet the conditions of BS1192, the system did not accept it, which meant that the contractor did not finish the work and could receive penalties instead of payment [5]. In contrast to the concept of BIM technology (it is the organization of flows of project-building and project-technological information) and the concept of iasu (integrated production management system), the CALs concept includes not only the impact of green production, but also all other stages, without solving applied design and planning problems.

The process of creating a complex object is characterized by an intensive exchange of results between organizations, divisions of the organization and specific performers involved in the development of the project. Joint, cooperative design and production of an object can be effective if it is based on a single green information model of the object. This task is relevant not only for stable production structures, but also for structures that are temporarily created for the purpose of implementing high-tech projects and fulfilling large orders, including research institutes, design bureaus, main contractors, subcontractors, suppliers, etc., geographically remote from each other, using incompatible computer platforms and software solutions. The lifetime of such a structure is determined by the time the order is completed or the life cycle of the product being created (buildings, structures, territories, etc.). In BIM terms, such a structure is called a virtual object. A virtual construction site is characterized by a common "information space" that provides, subject to appropriate standards, the sharing of information. The design and technological information model developed at this stage should be based on the use of the ISO 10303 step standard [1], [2]. Once created, the product model is used multiple times. Additions and changes are made to it, and it serves as a starting point for modernization. Compliance with the standard ensures correct interpretation of stored information.

ISO 10303 STEP is an evolving standard. Currently, the greatest progress has been made in the field of description of engineering products (ISO 10303-2203). The ideology of the ISO 10303 standard is that in addition to the basic elements (integrated resources), it includes so-called application protocols that define the specific structure of the information model for various subject areas (automotive, shipbuilding, construction, electronics, etc.). All application protocols (applied information models) are based on standardized integrated resources. This ensures continuity with existing solutions when creating a new application Protocol.

In accordance with ISO 10303, the object information model includes:

> Structure and composition of the product, including versions (modifications);

> Geometric models of object components (Foundation, enclosing structures, roof, part, Assembly unit, product) and their relationship based on TEI classifiers;

> > Design text, drawing and graphic documentation for the object as a whole and its components (technical tasks, sketches, work projects, design notes, drawings).

> Data about changes, approvals, and approvals.

Using a standard method for presenting design and technological data allows you to solve the problem of information exchange between different divisions of the enterprise, as well as cooperation participants equipped with heterogeneous design systems. Standardization of the data format makes it possible to quickly transfer the functions of one contractor to another, which in turn has the opportunity to take advantage of the results of the work already done. This feature is especially important for objects that have a long life cycle, when it is necessary to ensure continuity of information support for the object, regardless of the current market or political situation.

The vast majority of modern computer-aided design systems (Unigraphics, Computervision, Euclid, ProEngeener, etc.) support working with data in STEP format. in addition, there are a number of commercial software products that provide data conversion from various data formats to STEP format, which creates objective prerequisites for building integrated information systems.

Modeling of life cycle of green innovation products in quality systems

Taking into account the complex structure of most enterprises, it is important to identify the main processes, as well as simplify and rank the processes depending on the management goals.

Where people need to manage multiple processes and their interactions, especially complex processes that may involve multiple operations, problems are likely to occur. One of the possible ways to identify these places and smooth out negative factors is to use the technology of business process analysis and reengineering BPR (Business Process Reengineering).

It should be noted that the quality system is implemented through processes that occur within the framework of functions that are combined and intersect with each other in the process of product life cycle. For a quality system to be effective, these processes and their associated responsibilities, powers, procedures, and resources must be defined and applied in a consistent manner. To be effective, a quality system requires coordination and compatibility of the component processes and the definition of their interfaces. The international standards of the ISO 9000 series are also based on the concept of LC products.

Impact of green innovative products on the environment

Creating eco-friendly products is the imperative of the times all over the world. The reference point for developers of new construction projects, first of all, should be national standards with the application of international standards ISO 14000. To meet these regulatory requirements, it is necessary to conduct an analysis and assessment of the object's housing and utilities from the point of view of environmental impact and, based on the results of the analysis, implement certain rules and regulations in order to minimize or even completely eliminate waste and garbage generated over the entire period of the object's existence, dispose of containers and packaging, etc., reduce energy and material consumption.

An important part of assessing the environmental impact of a construction project is to determine the environmental impact it causes. For such an assessment, it is necessary to provide developers with fairly simple and accessible methods for determining various types of environmental stress. Currently, such methods exist, in particular, to account for carbon dioxide emissions (which leads to global warming), sulfur and nitrogen oxides (which cause acid rain).

Environmental impact assessment is carried out for each stage of the life cycle of a construction object, including the purchase of raw materials, production, transportation and handling, operation, and disposal [6].

The solution of these problems is possible only with the help of effective information support, i.e., using CALS technology.

For the first stage, the volume of materials purchased for the production of products is estimated. In the second stage determine the cost of electricity, water, fuel, etc. On the stage quantities of consumables and energy. Integrated emissions of harmful and toxic substances are taken into account for all stages of the construction project life cycle.

Special attention should be paid to the evaluation and modeling stage of recycling, which takes into account the costs and, accordingly, the environmental load is generally associated with the transportation of waste, their processing, possibilities of recycling in the waste of raw materials, consumable and received (e.g., from waste incineration) energy.

Stages of Informatization of "green" standardization

The choice of a life cycle model in specific methodologies and technologies that implement them sets the division of the process of creating IP SOFTWARE into stages, stages (sub-stages) and operations. This allows you to plan and organize the process of collective development, monitor development progress and the management of this process, i.e. provides the manageability and predictability of the process of creating IP. Life cycle of IP is divided into stages, which are associated with the results of the core processes defined by ISO 12207.

The analysis of the life cycle models traditionally used in our country (GOST 34.601-90 for automated systems), and the most common in the West modern methodologies and models of the life cycle for IP, carried out within the framework of the system project, allowed us to form a life cycle model of green standardization, which combines our standardized development stages (with minor changes) and modern approaches to IP design, determining the current content of stages, works and results obtained at each stage.

Life cycle model defined by the methodology for the establishment OF green standards, includes the following basic stages of creation of IP:

1. System design: the analysis of the organization, analysis and adoption of the basic design decisions on architecture of IP, formation of information system requirements and tasks for the technical design and development of the IP, the formation of the business plan of the creation of IP (assessment of trudoemkost and other technical and economic indicators, a detailed schedule of the development); 2. Technical design: design of the is database, application software architecture, application interfaces, including with existing automation tools and other systems, and formation of requirements for applications and system-wide SOFTWARE; 3. Operational design: database creation, design, rapid development, testing, and application integration; 4. IP Testing; 5. Trial operation of IP; 6. Deployment, maintenance and development of IP.

3. CONCLUSIONS

Artificial intelligence is most relevant for use in the field of environmental protection and health.

In combination with mixed reality systems, cloud technologies and business optimization tools, it will become the basis for a large-scale transformation of the green innovative technological structure of the economy. Transparency and universal availability of green standards are engineering requirements for the development of innovative green technologies, as well as innovative green products.

The article defines the main methodological and organizational principles for creating and developing the legal framework for Informatization and standardization:

1. A system of basic principles of Informatization of green standardization has been Developed based on the analysis of international and national standards of Russia that regulate the conditions for building and functioning of the information educational environment and infrastructure for Informatization of green standardization.
2. The principles of building and applying profiles of green standardization automation objects based on the basic concept of the life cycle of green innovative products are Developed.
3. Systematized technologies for information support of the life cycle of green innovative construction projects of the energy industry and Rosatom Corporation, which are the basis for creating a regulatory framework for Informatization of green standardization.
4. The aspects of managing the impact of green innovative products on the environment and the most rational area of green design and green construction of objects are Considered.
5. The areas of technology for reengineering control systems for various processes in construction and the main stages and stages of Informatization, standardization and information system creation are Defined.

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REFERENCES

1. **Telichenko V.I., Slesarev M.Yu.** Logistics of innovations of environmentally safe construction objects//Bulletin of the Department of construction Sciences. Russian Academy of architecture and construction Sciences. No. 4 M 2001 From 183–189.
2. **Telichenko V.I., Slesarev M.Yu.** Information support. Basic terms and definitions. Study guide M. Ed. Association of construction universities, 2005. – 272 p.
3. **Kazakov, P.V**. Fundamentals of artificial intelligence: textbook. Manual / P. V. Kazakov, V.A. Shkaberin. – Bryansk: BSTU, 2007. – 196 p. – (Ser.Information systems and technologies). ISBN 5-89838-302-6
4. **Novikov F.A.** Artificial intelligence: knowledge representation and methods for finding solutions: Textbook. – SPb.: Publishing house of Polytechnical Institute. UN-TA, 2010. – 240 p. ISBN 978-5-7422-1845-6
5. **Talapov V.** "Fundamentals of BIM: introduction to building information modeling" Recommended by the NRO UMO of higher education institutions of the Russian Federation for education in the field of construction as a textbook for students of higher educational institutions studying in the specialty 270800 "Construction" Moscow, 2011 UDC 721.01: 004.9 BIM BBK 38.2+32.973.26-018.2 T16 Novosibirsk February, 2011. – 392 p.
6. **Nevmerzhitsky V.A.** Information support of decision of ecological problems//Secondary vocational education. No. 2, 2013, Pp. 54–56.

Publishing house: Union of Directors of secondary specialized educational institutions of Russia, Autonomous non-profit organization "editorial Board of the magazine "Secondary professional education"; (Moscow). ISSN: 1990-679X

7. **Schwab K.** The fourth industrial revolution / K. Schwab – "Eksmo", 2016- (Top Business Awards) ISBN 978-5-699-90556-0
8. **Shvab K., Davies N.** Technologies of the Fourth industrial revolution: [translated from English] / Klaus Shvab, Nicholas Davies": Eksmo; Moscow; 2018. – ISBN 978-5-04-095268-7
9. **Shlyapnikov V.V.** national intelligence Council of the United States on the paradox of progress// The fourth industrial revolution: realities and modern challenges. X anniversary Saint Petersburg sociological readings: proceedings of the International scientific conference, April 13–14, 2018, Saint Petersburg, Russia. – SPb.: Publishing house of Polytechnical Institute. UN-TA, – 2018. – 896 p.
10. Global Trends: PARADOX OF PROGRESS // A publication of the National Intelligence Council. URL: https://www.dni.gov/files/images/globalTrends/documents/GT-Full-Report.pdf(дата обращения: 21.01.2018)
11. **Telichenko V.I., Slesarev M.Yu.** "Green" standardization of the future-a factor of environmental safety of the life environment / / Industrial and civil construction, 2018, no. 8, Pp. 90–97. https://elibrary.ru/item.asp?id=35418173 date of reference: 28.10.19.
12. **Telichenko V.I., Slesarev M.Yu.** Green standardization of technologies for the formation of a natural environment of life// MGSU Bulletin (issue 5, 2018, pp. 558–567) http://vestnikmgsu.ru/index.php/ru/archive/article/display/186/1 accessed: 28.10.19.
13. **Gift Noah.** Pragmatic I. Machine learning and cloud technologies. – SPb.: Peter. 2019. – 304 p.: ill. – (Series "For professionals"). ISBN 978-5-4461-1061-2
14. **Slesarev M.Yu., Telichenko V.I**. Green standards of the life environment on the examples of world leading innovative companies// System engineering of construction. Cyberphysical construction systems-2019 [Electronic resource]: collection of materials of the all-Russian scientific conference (Moscow, November 25, 2019) / Ministry of science and higher education of the Russian Federation, national research Moscow state University of civil engineering. – Electron. Dan. I progr. (17 MB). – Moscow: MISI – MGSU Publishing house, 2019. – Access mode: http://mgsu.ru/resources/izdatelskayadeyatelnost/izdaniya/izdaniya-otkr-dostupa/ - title title. screens. ISBN 978-5-7264-2064-6
15. **Slesarev M.Yu., Telichenko V.I.** Review of norms, methods and models of Geoecology in aspects of problems of "green" standardization of construction// Geoecology. Engineering geology. Hydrogeology. Geocryology, 2020, no. 1, pp. 53-57 DOI: 10.31857/S0869780320010184

СПИСОК ЛИТЕРАТУРЫ

1. **Теличенко В.И., Слесарев М.Ю.** Логистика инноваций экологически безопасных строительных объектов//Вестник отделения строительных наук. Российская академия архитектуры и строительных наук. №4 М 2001 г. – С. 183–189.
2. **Теличенко В.И., Слесарев М.Ю.** Информационное обеспечение. Основные термины и определения. Учебное пособие М. Изд. Ассоциация строительных вузов, 2005 г. – 272 с.
3. **Казаков, П.В.** Основы искусственного интеллекта: учеб. Пособие / П.В. Казаков, В.А. Шкаберин. – Брянск: БГТУ, 2007. – 196 с. – (Сер.Информационные системы и технологии). ISBN 5-89838-302-6
4. **Новиков Ф.А.** Искусственный интеллект: представление знаний и методы поиска решений: Учеб. пособие. – СПб.: Изд-во Политехн. ун-та, 2010. – 240 с. ISBN 978-5-7422-1845-6

5. **Талапов В.** «Основы BIM: введение в информационное моделирование зданий» Рекомендовано НРО УМО вузов РФ по образованию в области строительства в качестве учебного пособия для студентов высших учебных заведений, обучающихся по специальности 270800 «Строительство» Москва, 2011 УДК 721.01:004.9BIM ББК 38.2+32.973.26-018.2 Т16 Новосибирск февраль, 2011. с.392
6. **Невмержицкий А.В.** Информационное обеспечение решения экологических задач// Среднее профессиональное образование. №2, 2013 г. – С. 54–56. Издательство: Союз директоров средних специальных учебных заведений России, Автономная некоммерческая организация "Редакция журнала "Среднее профессиональное образование"; (Москва) ISSN: 1990-679X
7. **Шваб К.** Четвертая промышленная революция / К. Шваб – «Эксмо», 2016 – (Top Business Awards) ISBN 978-5-699-90556-0
8. **Шваб К., Дэвис Н.** Технологии Четвертой промышленной революции: [перевод с англ/] / Клаус Шваб, Николас Дэвис»: Эксмо; Москва; 2018. ISBN978-5-04-095268-7
9. **Шляпников В.В.** Национальный совет по разведке США о парадоксе прогресса// Четвертая промышленная революция: реалии и современные вызовы. X юбилейные Санкт-Петербургские социологические чтения: сборник материалов Международной научной конференции, 13–14 апреля 2018 г., Санкт-Петербург, Россия. – СПб.: Изд-во Политехн. ун-та, 2018. – 896 с.
10. Global Trends: PARADOX OF PROGRESS // A publication of the National Intelligence Council. URL: https://www.dni.gov/files/images/globalTrends/documents/GT-Full-Report.pdf(дата обращения: 21.01.2018)
11. **Теличенко В.И., Слесарев М.Ю.** "Зелёная" стандартизация будущего – фактор экологической безопасности среды жизнедеятельности // Промышленное и гражданское строительство, 2018. – № 8, – С. 90–97. https://elibrary.ru/item.asp?id=35418173 Дата обращения: 28.10.19.
12. **Теличенко В.И., Слесарев М.Ю.** Зелёная стандартизация технологий формирования природоподобной среды жизнедеятельности// Вестник МГСУ (выпуск 5, 2018, с. 558-567) http://vestnikmgsu.ru/index.php/ru/archive/article/display/186/1 Дата обращения: 28.10.19.
13. **Гифт Ной**. Прагматичный ИИ. Машинное обучение и облачные технологии. – СПб.: Питер. 2019. – 304 с.: ил. – (Серия «Для профессионалов»). ISBN 978-5-4461-1061-2
14. **Слесарев М.Ю., Теличенко В.И.** Зеленые стандарты среды жизнедеятельности на примерах мировых лидирующих инновационных компаний// Системотехника строительства. Киберфизические строительные системы – 2019 [Электронный ресурс]: сборник материалов Всероссийской научной конференции (Москва, 25 ноября 2019 г.) / Министерствово науки и высшего образования Российской Федерации, Национальный исследовательский Московский государственный строительный университет. – Электрон. дан. и прогр. (17 Мб). – Москва: Издательство МИСИ – МГСУ, 2019. – Режим доступа: http://mgsu.ru/resources/izdatelskayadeyatelnost/izdaniya/izdaniya-otkr-dostupa/ – Загл. с титул. экрана. ISBN 978-5-7264-2064-6
15. **Слесарев М.Ю., Теличенко В.И.** Обзор норм, методов и моделей геоэкологии в аспектах проблем “зеленой” стандартизации строительства// Геоэкология. Инженерная геология. Гидрогеология. Геокриология, 2020, № 1, – с. 53–57 DOI: 10.31857/S0869780320010184

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THEORETICAL SUBSTANTIATION OF THE MECHANISM PATTERNS OF THE MANMADE BASE "STRUCTURAL GEOTECHNICAL SOLID"

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Abstract. When building on weak water-saturated soils, manmade base in the form of a "structural geotechnical solid" are increasingly used. The article provides a theoretical substantiation for the use of a model of a transversally isotropic material with the given deformation characteristics for the design of such structures. The problem of determining the radius of a rigid cylindrical element during its formation in an elastic-plastic porous medium under normal pressure of jet-grouting of soil is considered. A method is proposed for determining the effective modulus of deformation of a "structural geotechnical solid" with the allocation of a representative volume – a periodicity cell, within which the geometric averaging of deformation characteristics is performed depending on the volume contribution of its components. Analysis of the results of modeling the joint operation of the base-building system using the proposed base model showed the effectiveness of its application.

Keywords: weak water-saturated soil; structural geotechnical solid; jet-grouting

ТЕОРЕТИЧЕСКОЕ ОБОСНОВАНИЕ ЗАКОНОМЕРНОСТЕЙ ПОВЕДЕНИЯ ИСКУССТВЕННОГО ОСНОВАНИЯ «СТРУКТУРНЫЙ ГЕОТЕХНИЧЕСКИЙ МАССИВ»

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Аннотация. При строительстве на слабых водонасыщенных грунтах возрастающее применение находят искусственные основания в виде «структурного геотехнического массива». В статье приводятся теоретическое обоснование использования для проектирования таких конструкций модели транверсально-изотропной среды с приведенными деформационными характеристиками. Рассматривается задача определения радиуса жесткого цилиндрического элемента при формировании его в упруго-пластической пористой среде под нормальным давлением струйной цементации грунта. Предлагается методика определения эффективного модуля деформации «структурного геотехнического массива» с выделением представительного объема – ячейки периодичности, в пределах которого выполняется геометрическое усреднение деформационных характеристик в зависимости от объемного вклада его составляющих. Анализ результатов моделирования совместной работы системы основание-здание с использованием предлагаемой модели основания показал эффективность ее применения.

Ключевые слова: слабый водонасыщенный грунт; структурный геотехнический массив

INTRODUCTION

Artificial bases are used in cases where compliance with regulatory requirements for limiting the difference in the settlement of foundations of buildings and structures is not ensured, or this is technically difficult and economically ineffective [1–4]. In weak water-saturated soils, artificial bases are increasingly used in the form of a structural geotechnical solid [5, 6]. The study of the state of the art has shown that the choice of design methods and the technology of artificially improved bases in most cases is carried out experimentally on the construction site and the obtained solution was not always optimal [7]. In this regard, the development, on the basis of experimental and theoretical studies, of the calculation and design methodology for one of the types of artificial bases with specified physical and mechanical characteristics – "structural geotechnical solid" is an urgent problem.

The structure of the structural geotechnical solid (Fig. 1) consists of a weak initial soil (2), rigid reinforcing soil-concrete elements (1) and a flexible distribution grillage (3) [8].

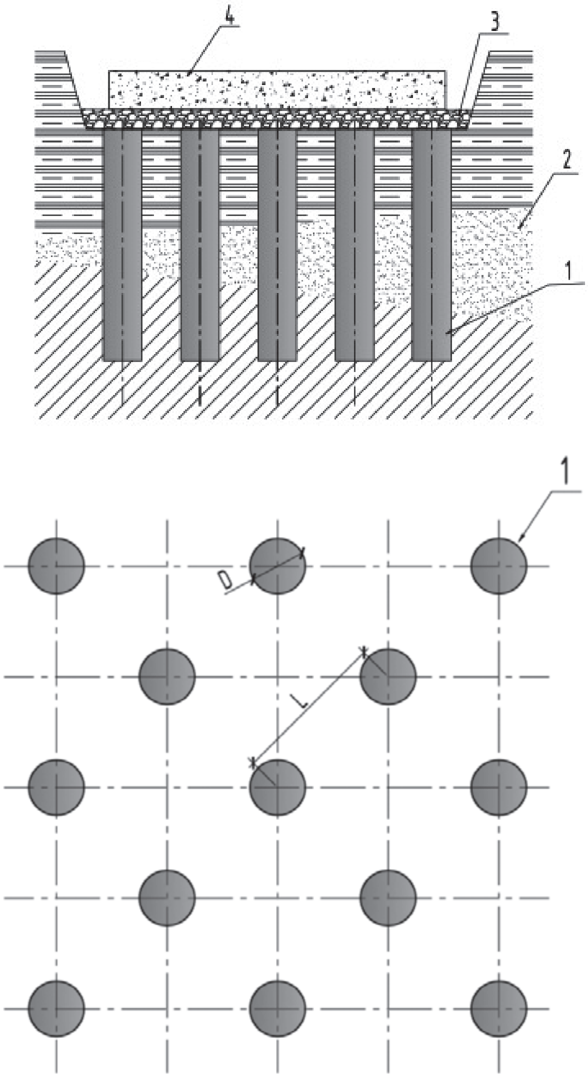


Figure 1. Construction of an artificial foundation "structural geotechnical solid"

In the course of modeling the joint operation of the building-foundation-base system, the required diameter (D) and the spacing of the reinforcing elements (L) are determined.

In this paper, an artificial base is considered, reinforced with vertical rigid cylindrical elements, performed using the technology of jet grouting of the soil [9.10].

1. MODEL OF VERTICALLY REINFORCED SOIL BASE - STRUCTURAL GEOTECHNICAL SOLID

The base model should be adequate for the accuracy of the initial data and the required accuracy of the final results of the calculation of the "building-foundation-base" system [11]. Due to the large variety of types of base soils, conditions for the addition of solids, etc., none of the existing models is universal and is used only for certain specific types of soils.

To construct a mechanical model of "structural geotechnical solid", we apply the approach used in geomechanics to describe the behavior of a rigid body with a structure [12].

"Structural geotechnical solid" is represented as an ideal continuous medium, the deformations of which are linear with respect to external forces, if only the internal stresses in the soil do not exceed the limiting values. At the same time, in a solid body, heterogeneities (soil-concrete reinforcing elements) are evenly scattered over the volume, and the distance between them is much larger than their own size. These inhomogeneities are responsible for irreversible deformations: stresses are concentrated on them and they relax in time. Let us accept this mechanism of energy dissipation as the only one.

Taking into account that inhomogeneities occupy a small fraction of the volume, the deformations of the structural geotechnical solid have been characterized only by the values averaged over space. The uneven distribution of stresses within the geotechnical solid qualitatively distinguishes the proposed model: they consist of two components – general stresses caused by a change in volume or distortion of the shape and local stresses on inhomogeneities.

At high rates of deformation, stresses on inhomogeneities lead to an increase in the rigidity of the structural geotechnical solid, and under dynamic influences, to an increase in effective strength ("dynamic strength"). The proposed mechanical model of "structural geotechnical solid" allows us to consider classical problems of determining stresses and deformations arising under the influence of external forces, but not limited to finding equilibrium parameters, since after the application of a load in the soil mass, irreversible deformations and stress relaxation on inhomogeneities continue.

In this case, to describe the behavior of the "structural geotechnical solid", one can use the models of the linear theory of elasticity and the creep model, and also consider the process of attenuation of elastic seismic waves.

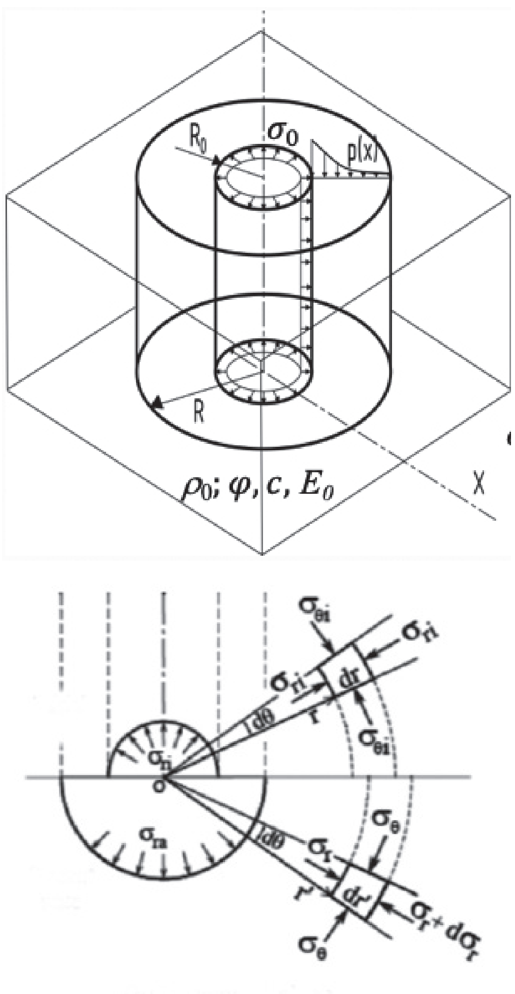


Figure 2. Design diagram of the problem of forming a cylindrical element

2. CYLINDRICAL ELEMENT SIZE IN ELASTIC MEDIUM

One of the main theoretical problems is to determine the required radius of a soil-concrete element in an elastic-plastic porous medium under the action of normal pressure of jet cementation (σ_0). In the papers [13, 14], analytical solutions to the problem of the development of a cylindrical well are given taking into account the elasticity and plasticity of materials. The problem was considered when a hard core penetrated into a soil environment. Let us apply the development of these solutions to the problem of the formation of a soil-concrete element in a soil environment during jet grouting. Let us determine the size of the expansion zone taking into account the final deformations and the dependence of the yield point on pressure.

Figure 2 shows the calculation scheme of the problem. The soil medium is characterized by an initial density – ρ_0; internal friction angle – φ; specific adhesion – with and modulus of deformation E_0.

In order to find the boundary between the area of plastic yield and the area of elastic compression of the porous medium under the action of jet grouting pressure, the motion of a material particle of a cement solution in a soil medium is considered, described by the following equation:

$$\rho_0 r \frac{\partial \upsilon}{\partial t} = x \frac{\partial \sigma_r}{\partial r} + (\sigma_r - \sigma_\theta) \frac{\partial x}{\partial r} \qquad (1)$$

Joint solution of the system of physical equations of state of the medium:

- for an elastic area

$$\frac{\partial S_i}{\partial t} = 2G \left(\frac{\partial \varepsilon_i}{\partial t} + \frac{1}{3\rho} \cdot \frac{\partial \rho}{\partial t} \right) \qquad (2)$$

- for a plastic area

$$\sigma_r - \sigma_\theta = -\tau_0 + \mu(\sigma_r + \sigma_\theta);$$
$$\tau_0 = 2c \cdot cos\varphi; \;\; \mu = sin\varphi. \qquad (3)$$

and the closing equation of the soil medium:

$$p = 3K\varepsilon_p \frac{\ln\rho_0 - \ln\rho}{\ln\rho_0 - \ln\rho - 3\varepsilon_p} = K\left(\frac{\rho_0}{1-\rho}\right) \quad (4)$$

allows you to obtain the equation of the separation boundary of the plastic and elastic zones from the relation

$$\frac{\partial x}{\partial r} = \frac{r}{x}\left[1 + \frac{3\varepsilon_p p(x)}{p(x)+3K\varepsilon_p}\right] \quad (5)$$

By integrating the equation over a unit volume, we obtain the dependence of the radius on the volumetric modulus of deformation and the reduced strength of the original soil:

$$R = \frac{C}{\sqrt{K}}\text{; where: } C = 1{,}497\,\tau_0^{-0{,}113} \quad (6)$$

Analysis of the solution shows that with an increase in the volumetric modulus of deformation, the size of the expanded cavity decreases (Fig. 3).

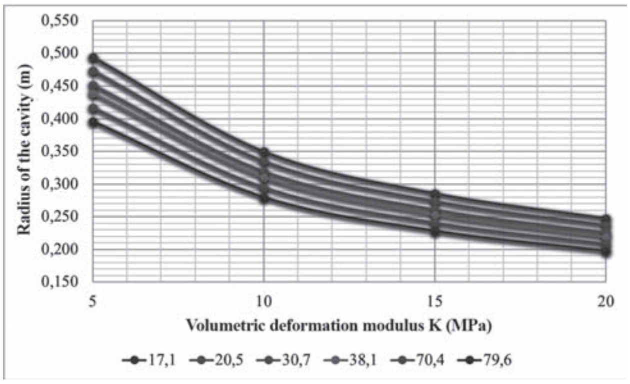


Figure 3. Graph of the change in the radius of the expandable cavity depending on the volumetric deformation modulus (K) and the reduced resistivity (τ_0)

This behavior can be explained by different values of soil porosity; in more porous soil, the expansion of the cavity occurs due to the elimination of pores in the plastic region, which leads to a rapid drop in the effective pressure with an increase in the cavity radius and the formation of a small zone of plastic deformation.

The obtained solution to the problem of static expansion of a cylindrical cavity in an elastoplastic compressible medium, taking into account the nonlinear compressibility, makes it possible to calculate the theoretical diameter of a soil-concrete element depending on the physical and mechanical properties of soils.

3. DETERMINATION OF EFFECTIVE DEFORMATION CHARACTERISTICS OF A STRUCTURAL GEOTECHNICAL MASSIVE

The base, reinforced with vertical elements at axial distances of no more than three diameters, is a composite system consisting of a soft and pliable matrix (soil) and rigid reinforcing (soil-concrete) elements. In this case, most of the external load is absorbed by the soil matrix. To describe the behavior, a continuum hypothesis is introduced, which includes the averaging procedure, through which the structure and state of the material are idealized in such a way that the material is considered homogeneous, for which the characteristic properties inherent in a homogeneous medium are the same at all points. The main task is to use the averaging procedure to predict the effective properties of an idealized homogeneous medium in terms of phase properties and geometric characteristics. We consider the "structural geotechnical solid" as a two-dimensional periodic medium – a fibrous unidirectional composite, which is a periodic system of parallel cylindrical fibers immersed in a homogeneous matrix, the characteristics of the physical and mechanical characteristics of which are different from the characteristics of the fibers (Fig. 4). Based on the structure of a unidirectional composite with hexagonal fiber packing and according to the continuum hypothesis, the material can be considered a homogeneous medium with an axis of elastic symmetry coinciding with the direction of the fibers, i.e., is a transversely isotropic material [15].

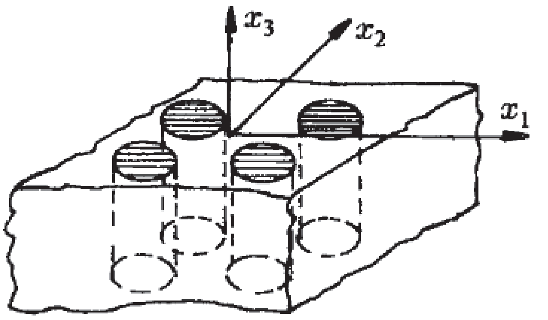


Figure 4. Two-dimensional periodic medium – fibrous unidirectional composite

Thus, the elastic behavior of the composite is characterized by five independent constants: elastic moduli E_1 and E_2 corresponding to the directions along and across the fibers, Poisson's ratios v_{12} and v_{23}, and the operator shear modulus G_{12}.

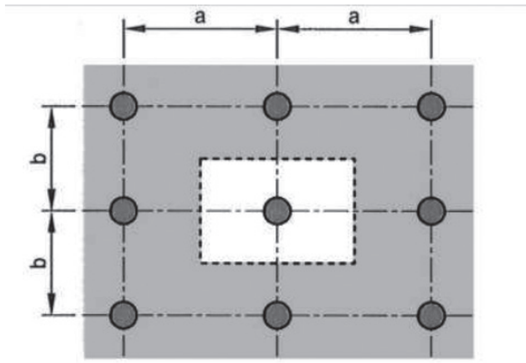
We select a periodicity cell in it – a representative volume with a characteristic size of inhomogeneity, within which the properties can be averaged. The scale of the representative volume should be much larger than the characteristic size of the inhomogeneity and small in comparison with the characteristic size of the body (Fig. 5). Under these conditions, a heterogeneous material can be idealized, considering it as equivalent to a homogeneous material with properties averaged over a representative volume [16]. Within the boundaries of the periodicity cell, the gradient of external influences (pressure) changes insignificantly.

The condition for the correct selection of the effective characteristics of the structural geotechnical solid is the equality of the average deformations of the selected heterogeneity cell when simulating it with individual elements and a single array.

We introduce two specific parameters

– the coefficient of reinforcement, characterizing the volume fraction of reinforcing elements in the soil mass:

$$\propto = V_r / V_s \tag{7}$$



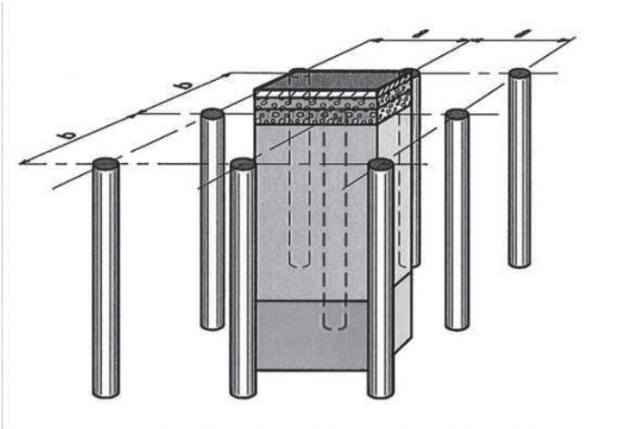


Figure 5. Allocation of the periodicity cell in the structure of the structural geotechnical solid

where V_S is volume of soil reinforced; V_r is volume of reinforcing elements and ratio of deformation moduli:

$$\eta = E_s / E_r. \tag{8}$$

where E_s, E_r are calculated values of the modulus of elasticity of reinforcing elements and the modulus of soil deformation.

The reinforcement coefficient is a function of the diameter of the soil-concrete elements (D) (variation range 1.0 ... 1.2 m) and the distance (L) between the element axes (variation range 2 ... 3 D).

The ratio of the deformation moduli is determined for the most widely used initial range of the deformation modulus of the fixed soil (5.0 ... 20.0 MPa).

In this case, the effective modulus of deformation of the structural geotechnical solid (E_{sgs}) along the axis coinciding with the direction of reinforcement can be determined by geometric averaging according to Voigt [17]:

$$E_{sgs} = \propto E_r + (1-\propto)E_s \qquad (9)$$

CONCLUSIONS

The fundamental difference of the proposed model lies in the use of a homogeneous medium with effective characteristics, which replaces the field of elements with interelement soil mass and significantly reduces the time required for calculating the mechanical behavior of a large number of variants of foundation structures. Comparative analysis of patterns of distribution of vertical displacements of the base, determined by this model, shows that the average absolute values differ within 5 ... 10 percent from the model with selected reinforcing elements, and are within the accuracy of engineering calculations. Consequently, the application of the "structural geotechnical solid" model, taking into account the reduced stiffness of the underground part of the building, is quite sufficient to determine the final stabilized settlement of the building and will be further considered as the main design scheme.

REFERENCES

1. **Travush V.I., Shulyatev S.O.** Adjusted pile foundation construction for skyscrapers // VII international symposium "Actual problems of computational simulation in civil engineering", 2018, pp.012008
2. **Cytovich, N.A.** Osnovy prikladnoj geomekhaniki v stroitel'stve [Fundamentals of applied geomechanics in construction]/ N.A. Cytovich Z.G.Ter-Martirosyan, M: Vyssh. shkola,1981, 317 p.
3. **Abelev, M.YU**. Stroitel'stvo promyshlennyh i grazhdanskih sooruzhenij na slabyh vodonasyshchennyh gruntah [Construction of industrial and civil structures on weak water-saturated soils] / M.YU. Abelev, Strojizdat, 1983, 248 p.
4. **Bartolomey A.** Geotechnical trends in urban terrains evolution/ A. Bartolomey, O.Makovetsky , A. Ponomaryov, V. Ofrikhter / Geotechnical problems with man-made and man influenced grounds // XIII-th European Conference on Soil Mechanics and Geotechnical Engineering, Prague, 2003.
5. **Konovalov, P.A.** Raschet effektivnosti ukrepleniya slabyh osnovanij nagruzheniem, drenirovaniem i armirovaniem [Calculation of the effectiveness of strengthening weak foundations by loading, drainage and reinforcement] / P. A. Konovalov, F. F. Zekhniev, S.G. Bezvolev // Osnovaniya, fundamenty i mekhanika gruntov. 2003, no.1, pp. 2–8.
6. IREX Recommandations pour la conception, le dimensionnement, l'exécution et le contrôle de l'amélioration des sols de fondation par inclusions rigides. – ASIRI 384, Presses des Ponts, 2012.
7. **Mangushev, R.A.** Ustrojstvo i rekonstrukciya osnovanij i fundamenta na slabyh i strukturno-neustojchivyh gruntah[]./ R.A. Mangushev, R.A. Usmanov, A.I. Osokin. – SPb.: Izd. Lan', 2018,460 p.
8. **Makovetski, O.** Application of Jet Grouting for Installation of Substructures of Estates/ O. Makovetski // Procedia Engineering.,2016, Vol. 150 : International Conference on Industrial Engineering (ICIE-2016), pp. 2228–2231.
9. **Dzhantemirov, H.A.** Opyt usileniya osnovaniya sooruzheniya s pomoshch'yu strujnoj geotekhnologii/[Experience in strengthening the Foundation of a structure using jet Geotechnology] H.A. Dzhantemirov, A.A. Dolev // Osnovaniya, fundamenty i mekhanika gruntov, 2006, no.1, pp. 16–19.
10. **Kashevarova, G.** Analysis of Experimental and Estimated Jet-grouted Soil Mass Deformations/ G. Kashevarova, O. Makovetskiy // Procedia Engineering, 2016, Vol. 150 : International Conference on Industrial Engineering. – pp. 2223–2227.
11. **Bondarenko V.M., Fedorov V.S.** Modeli pri reshenii tekhnicheskih zadach [Models for

solving technical problems]// Perspektivy razvitiya stroitel'nogo kompleksa, 2014, pp. 262–267.

12. **Rodionov, V.N.** Osnovy geomekhaniki [Fundamentals of geomechanics] / V.N. Rodionov, I.A. Sizov, V.M. Cvetkov, Nedra,1986, 301 p.
13. **Aptukov V.N., Hasanov A.R**. Rasshirenie cilindricheskoj polosti v szhimaemoj uprugoplasticheskoj srede [Expansion of a cylindrical cavity in a compressible elastic-plastic medium] // Vestnik Permskogo nacional'nogo issledovatel'skogo politekhnicheskogo universiteta. Mekhanika. – 2017, Vol.1., pp. 5–23.
14. **Yu, H.-S.** Cavity expansion methods in geomechanics/ H.-S.Yu. - Dordrecht; Boston: Kluwer Academic Publishers, 2010, 385 p.
15. **Ding, H.** Elasticity of transversely isotropic materials / H. Ding, W. Chen, L. Zang. – Springer,2 006, 444p.
16. **Karech, T.** Analysis by homogenization method of structures in reinforced soil and behavior interfaces of soil reinforcement / T. Karech // Journal of Civil Engineering and Construction Technology, 2012, Vol. 3(1), p. 17–24.
17. **Kristensen, R.** Vvedenie v mekhaniku kompozitov[Введение в механику композитов]/ R.Kristensen. – M.: Mir, 1982. – 331 p.

СПИСОК ЛИТЕРАТУРЫ

1. **Travush V.I., Shulyatev S.O.** Adjusted pile foundation construction for skyscrapers // VII international symposium "Actual problems of computational simulation in civil engineering", 2018, pp.012008
2. **Цытович, Н.А.** Основы прикладной геомеханики в строительстве / Н.А. Цытович З.Г.Тер-Мартиросян. – М: Высш.школа, 1981. – 317 с.
3. **Абелев, М.Ю.** Строительство промышленных и гражданских сооружений на слабых водонасыщенных грунтах / М.Ю. Абелев. – М.: Стройиздат, 1983. – 248с.
4. **Bartolomey A.** Geotechnical trends in urban terrains evolution/ A. Bartolomey, O.Makovetsky , A. Ponomaryov, V. Ofrikhter / Geotechnical problems with man-made and man influenced grounds // XIII-th European Conference on Soil Mechanics and Geotechnical Engineering, Prague, 2003.
5. **Коновалов, П.А.** Расчет эффективности укрепления слабых оснований нагружением, дренированием и армированием / П. А. Коновалов, Ф. Ф. Зехниев, С.Г. Безволев // Основания, фундаменты и механика грунтов. – 2003. – №1. – С. 2–8.
6. IREX Recommandations pour la conception, le dimensionnement, l'exécution et le contrôle de l'amélioration des sols de fondation par inclusions rigides. – ASIRI 384, Presses des Ponts, 2012.
7. **Мангушев, Р.А.** Устройство и реконструкция оснований и фундамента на слабых и структурно-неустойчивых грунтах: Научное издание./ Р.А. Мангушев, Р.А. Усманов, А.И. Осокин. – СПб.: Изд. Лань, 2018. – 460 с.
8. **Makovetski, O.** Application of Jet Grouting for Installation of Substructures of Estates/ O. Makovetski // Procedia Engineering. – 2016. – Vol. 150 : International Conference on Industrial Engineering (ICIE-2016). – P. 2228–2231.
9. **Джантемиров, Х.А.** Опыт усиления основания сооружения с помощью струйной геотехнологии/ Х.А. Джантемиров, А.А. Долев // Основания, фундаменты и механика грунтов. – 2006. – №1. – С.16–19.
10. **Kashevarova, G.** Analysis of Experimental and Estimated Jet-grouted Soil Mass Deformations/ G. Kashevarova, O. Makovetskiy // Procedia Engineering. – 2016. – Vol. 150 : International Conference on Industrial Engineering. – P. 2223–2227.
11. **Бондаренко В.М., Федоров В.С.** Модели при решении технических задач // Перспективы развития строительного комплекса. – 2014. – с. 262–267.
12. **Родионов, В.Н.** Основы геомеханики / В.Н. Родионов, И.А. Сизов, В.М. Цветков. – М.: Недра, 1986. – 301 с.

13. **Аптуков В.Н., Хасанов А.Р.** Расширение цилиндрической полости в сжимаемой упругопластической среде // Вестник Пермского национального исследовательского политехнического университета. Механика. – 2017. – №1. – С. 5–23.
14. **Yu, H.-S.** Cavity expansion methods in geomechanics/ H.-S.Yu. - Dordrecht; Boston: Kluwer Academic Publishers, 2010. – 385 p.
15. **Ding, H.** Elasticity of transversely isotropic materials / H. Ding, W. Chen, L. Zang. – Springer, 2006. – 444p.
16. **Karech, T.** Analysis by homogenization method of structures in reinforced soil and behavior interfaces of soil reinforcement / T. Karech // Journal of Civil Engineering and Construction Technology. – 2012. – Vol. 3(1), p. 17–24.
17. **Кристенсен, Р.** Введение в механику композитов/ Р. Кристенсен. – М.: Мир, 1982. – 331 с.

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SETTING UP A PROBLEM OF AIR-BORNE SOUND INSULATION CALCULATION FOR DOUBLE LAYER MASSIVE ENCLOSURES ON THE BASE OF THE MODELS WITH THE CONCENTRATED PARAMETERS

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Abstract. The calculation methods on the base of the concentrated parameters models, which were formed in the XX century, allowed to get simple and theoretically consistent solutions for the problems of one-layered building partitions sound insulation finding. The sound insulation estimation for the double-layered massive building partitions also is of scientific and practical interest, as double layer partitions are the particular case of the single layer enclosure's application. The concept of concentrated parameters includes the concentrated and the reduced masses, as well as the concentrated elasticity. The criteria for the object application as a specified kind of the concentrated parameters in the acoustical problems is the presence or the absence of the oscillation movement in it. The three calculation models with the application of the concentrated (discreet) parameters that to define the sound insulation of the massive double layer enclosures are given. The equations for sound insulation computation for one layer partition are represented. They were derived on the base of momentum law and energy conservation formulas under the continuity of energy flow conditions at the interface of different media. The three main paths of sound propagation from the room with the air-borne noise to the isolated room are shown. The two frequency range are separated on the way of the direct sound propagation: at the first, the surface density of the one of two layers and the air elasticity in the inter-layer gap influence on isolation; at the second one, the predominant role belongs to the summarized insulation by the "Mass Action Law" of the two layers. The indirect way's insulation is taken in account through the additional sound insulation graph drawing. The compound insulation curve is defined by the ways, where the sound energy transmittance is maximal at the standard frequency spectrum. The method of sound insulation calculation for the double layer partitions on the base of the concentrated parameters model application is revealed. As an example, the calculation of a prefabricated double layer inter-flat wall in the panel building was performed.

Keywords: limit frequency, sound insulation of the double layer massive partitions, discreet parameters, reduced mass, concentrated mass, concentrated elasticity, "Mass Action Law", coefficient of the oscillation velocity transmittance, free oscillation frequency, wave resonances

ПОСТАНОВКА ЗАДАЧИ РАСЧЁТА ЗВУКОИЗОЛЯЦИИ ВОЗДУШНОГО ШУМА ДВУХСЛОЙНЫМИ МАССИВНЫМИ ОГРАЖДЕНИЯМИ НА ОСНОВЕ МОДЕЛЕЙ С СОСРЕДОТОЧЕННЫМИ ПАРАМЕТРАМИ

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Аннотация. Созданные в конце XX века расчётные методики на основе использования моделей с сосредоточенными параметрами позволили получать простые и теоретически не противоречивые решения задач по нахождению звукоизоляции однослойных строительных перегородок. Нахождение звукоизоляции двойных массивных строительных перегородок, частного случая использования однослойных звукоизолирующих преград, также представляет научный и практический интерес. Под понятием сосредоточенных параметров подразумеваются сосредоточенная и приведённая массы, а также, сосредоточенная упругость. Критерием использования объекта в акустических задачах в качестве того или иного вида сосредоточенных параметров в заданном частотном диапазоне является отсутствие или наличие в нём волнового движения. Приведены три расчётные модели с использованием сосредоточенных (дискретных) параметров необходимые для вычисления звукоизоляции двухслойных массивных перегородок. Представлены выражения для нахождения звукоизоляции однослойных перегородок, полученные на основе применения уравнений сохранения количества движения и кинетической энергии с учётом свойств непрерывности передачи звуковой энергии на границе различных сред. Показаны основные пути распространения звука из помещения с источником в изолируемое помещение. При расчёте звукоизоляции по прямому пути выделяются два частотных диапазона: в первом, влияние на звукоизоляцию оказывает поверхностный вес одного из слоёв и упругость воздуха в воздушном промежутке; во втором определяющее значение играет суммарная звукоизоляция по закону «массы» каждого из слоёв. Звукоизоляция на косвенных путях распространения звука учитывается через построение графика добавочной звукоизоляции. Результирующий график звукоизоляции определяется теми путями, где возможно максимальное прохождение звука в нормируемом частотном диапазоне. Дана методика расчёта звукоизоляции массивных двойных строительных перегородок на основе применения моделей с сосредоточенными параметрами. В качестве примера, выполнен расчёт сборной двойной межквартирной стены в панельном здании.

Ключевые слова: предельная частота, звукоизоляция двухслойных массивных перегородок, дискретные параметры, приведённая масса, сосредоточенная масса, сосредоточенная упругость, закон «массы», коэффициент прохождения колебательной скорости, частота свободных колебаний, волновые резонансы

1. INTRODUCTION

The theory and the methods of practical engineer solutions for the sound insulation problems of envelope building constructions are permanently developing and improving, that is confirmed by the scope of nowadays issues on this topic [1–6]. The theory of the sound insulation calculation on the base of concentrated (discreet) parameters, which was founded at the end of the XX century is the one from their contemporary range.

As it is shown in papers [7–17], the calculation methods, that are based on the fundamental concepts of this theory, give the consistent, close to experiment, results for the computation of the single-layered building partitions sound insulation. Besides, some essential problems of building acoustics were managed to revise in the frame of this approach, for instance, such as insulation's value dependence from the noise incidence angle at the plate, the spatial and frequency resonances existence, and the internal friction coefficient's influence on the enclosure's insulation.

A particular case for the massive single-layered building partitions application is the double-layered sound protective structures for the purpose of acoustic comfort level increasing at the isolatable premises. Along with such decisions, the massive walls and partitions constructions, which have two rigid and shape generating strata divided by the air gap, are often provided.

The evaluation of a similar enclosure's insulation accordingly the classical sound insulation theory is theoretically and practically complicated, that's why the normative codes represent it in a mere approximation. Therefore, it seems interesting to set a task and to develop an algorithm for the engineering computation of massive double layered partitions on the basis of the physical models with the concentrated parameters.

2. MATERIALS AND METHODS

The problem of the calculation graph's obtaining for the double-layered massive envelopes is compounded by the impact of the indirect noise propagation paths through the contiguous structures. The three main paths of sound propagation in an insulated room can be derived in case of observing calculation model, fig. 1: A – is the direct way of sound transmittance through the double enclosure; B – is the sound transmittance through the rigid layers and the floor slab; C – is the sound propagation through the floor slab only. The real measurement's practice shows, that the sound insulations values by the way of the maximal sound propagation energy in a isolatable unit should be taken into consideration.

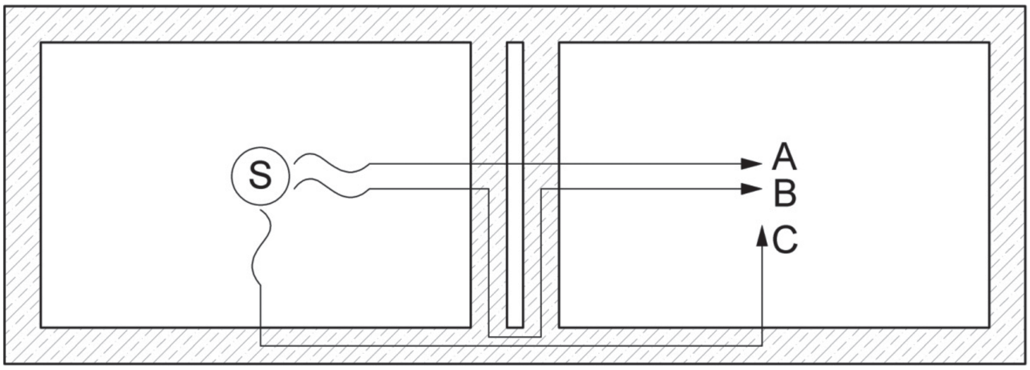


Figure 1. The sound propagation paths from the room with the source (S) in the protectable room: A – is the way of direct propagation; B and C – are the way of indirect transmittance through the adjoining constructions

The papers [10, 13, 15, 17] inform, that the objects can be either the environment for the wave moving's transmittance, that way they become to be "waveguides", or can be represented in the capacity of "concentrated masses" or "concentrated elasticity bodies". The criteria of construction's transition from the working in a "mass" or "elasticity" regime to the regime of a "waveguide" is written by the equation (1):

$$f_{ult.} = \frac{c}{2\pi l}, \ \text{Hz}; \qquad (1)$$

where $f_{ult.}$ – is an ultimate oscillation frequency, Hz, above which the wave movement can't be avoided; l – is the dimension of an object, along which the sound wave propagates, [m]; c – is the propagation velocity of the definite wave type in the object, [m·s^{-1}].

Thus, under the condition of $f < f_{ult.}$ a body is taken into account as the concentrated mass, which is defined by the surface density, m, [kg·m^{-2}]; or it can be taken as the concentrated elasticity, which is characterized by the elastic ratio, K, [N·m^{-1}]. At the range of $f > f_{ult.}$, the body becomes to be a guide to the mechanical waves, and, as it follows from the papers [9, 10, 13, 15], is denoted through the so called "reduced mass", μ, in the acoustical tasks. The reduced mass is inherently the mass fragment, that is limited by the wave length λ and multiplied on the reduction factor [1·(2π)$^{-1}$]:

$$\mu = \frac{\rho \cdot \lambda}{2\pi} = \frac{\rho \cdot c.}{2\pi f}, \ [\text{kg·m}^{-2}], \qquad (2)$$

where ρ – is the medium density, [kg·m^{-3}]; c and λ – are the propagation velocity, [m·s^{-1}], and the wave length of given form (dilatational, flexural or shear), [m]; f – is the oscillation frequency, [Hz]. Different combinations of introduced objects are possible by the way of a sound waves propagation in the acoustical problems. The figure 3 shows the most typical schemes of the sound propagation in double layer enclosures at the figure 2.

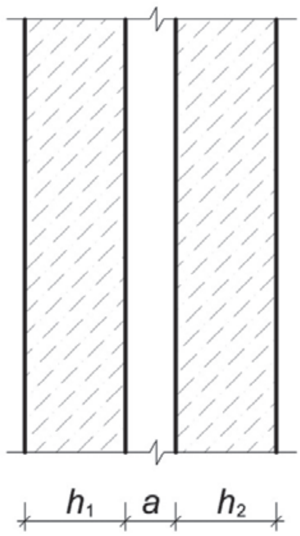


Figure 2. The scheme of a double layer massive partition

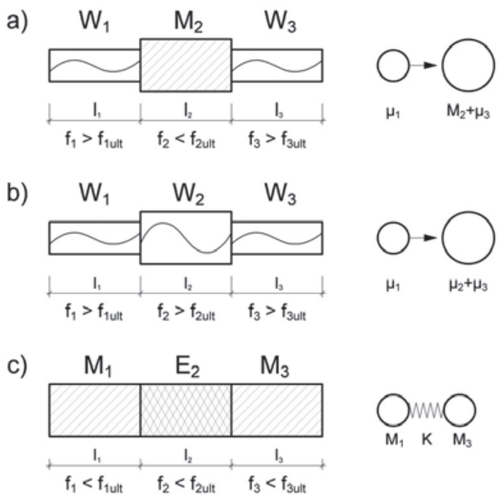


Figure 3. The schemes and the calculation models (at the right) with the concentrated parameters concerning to this issue: a – is waveguide (W_1)-mass (M_2)-waveguide (W_3); b – is waveguide (W_1)-waveguide (W_2)-waveguide (W_3); c – is mass (M_1)-elasticity (E_2)-mass (M_3); μ_1, μ_2, μ_3 – are the reduced masses of the objects; K – is the elastic ratio for the resilient layer

As it is described at the [10, 12, 13, 14, 17], it becomes possible to apply the momentum conservation law and the energy conservation law in acoustical processes after the introducing of concentrated parameters and under the condition of energy flow continuing at the interface of two media. Then, the scheme "a", figure 3, is applicable to the one-layered partition at the frequency range before so called "a wave coincidence phenomenon" [18, 19]: the air at the both sides of the structure is represented by the reduction masses μ_1, μ_3 and the partition is a concentrated mass M_2. The reduction mass of the air virtually strikes both the concentrated mass of the envelope and the reduction mass of the air over it.

Mathematically it can be written in the form of the equations (3) and (4) with the application of unit velocity and coefficients of sound transmittance and reflection:

$$\mu \cdot v = \mu \cdot v \cdot \beta + (\mu + m) \cdot v \cdot \alpha; \qquad (3)$$

$$\frac{\mu \cdot v^2}{2} = \frac{\mu \cdot (\beta v)^2}{2} + \frac{(\mu + m)\cdot(\alpha v)^2}{2}; \qquad (4)$$

where v – is the unite velocity of the media fragment movement; β – is the reflection coefficient of energy from the media fragment action on the plate surface; α – is the transmission coefficient of energy propagation into the plate from the moving media fragment; μ – is the reduction mass (in this case of the air); m – concentrated mass (of the building envelope).

The solution of this system gives the transmission coefficient of the oscillation velocity, α:

$$\alpha = \frac{2\mu}{2\mu + m} \qquad (5)$$

Then, according to the physical definition of the sound insulation, the equation (6) is derived. And it's form is very close to the formula of the "Mass Action Law":

$$R_{\text{M.A.L.1}} = 10lg\frac{1}{\alpha^2} = 10\lg\left(1 + \frac{m}{2\mu_a}\right)^2 = 10\lg\left(1 + \frac{\pi m}{\rho_0 \lambda_0}\right)^2 = = 10\lg\left(1 + \frac{\pi m f}{\rho_0 c_0}\right)^2, \text{[dB]}; \qquad (6)$$

where α – is the transmission coefficient of the oscillation velocity into the plate; f – is the current frequency, [Hz]; m – is the surface density of the plate, [kg·m^{-2}]; ρ_0 – is the air specific weight, [kg·m^{-3}]; c_0 – is the sound speed in the air, [m·s^{-1}]; μ_a – is the reduced mass of an air, [kg·m^{-2}].

After the wave coincidence frequency, f_L, the partition is working by the scheme "b" in the figure 3: the air from both partition sides is also represented as the masses μ_1 and μ_3, and the partition becomes to be the "waveguide" with the reduction mass μ_2. This time, the reduction mass of the air virtually strikes both the reduction mass of the envelope and the reduction mass of the air over it. After the similar form of the system consisting from the momentum conservation law and the energy conservation equations, the formula (7) is obtained. It characterizes the sound insulation by the "Mass Action Law" after the wave coincidence frequency.

$$R_{\text{M.A.L.2}} = 10lg\frac{1}{\alpha^2} = 10\lg\left(1 + \frac{\mu_{pl.}}{2\mu_a}\right)^2 = = 10\lg\,(1 + \frac{fm}{2\rho_0 c_0})^2, \text{[dB]}; \qquad (7)$$

where $\mu_{pl.}$ – is the reduced mass of the partition material, [kg·m^{-2}].

The equations (6) and (7) allow to find sound insulation values at the two conventionally distinguishing frequency ranges of the standard spectrum. The third range begins from the frequency of 65 [dB] in the engineer designs. The shear and the dilatational waves play a predominant role here for insulation defining, against the flexible waves at the previous ranges. Accordingly the normative documents, the graph is shown as a horizontal straight line at the third frequency range.

It is well known, that the resonance phenomena have an influence on the insulation figures at the definite frequencies. The resonances appear each times, when the integer number of semi-length flexible waves place by the length or by the width of the isolating plate. The resonance correction can be taken near 6 [dB] in average during the engineer calculation performing. The simple formulas (8), (9) are derived in case of air environment, minus resonance corrections, from the formulas (6), (7) respectively, that to draw the insulation graphs.

$$R_{\text{M.A.L.1}} = 20\lg mf - 48, \text{[dB]}; \qquad (8)$$
$$R_{\text{M.A.L.2}} = 20\lg mf - 58, \text{[dB]}. \qquad (9)$$

Let's consider the noise propagation by the path "A". The masses of the separate layers and the elasticity of air between them make their contribution to the insulation values simultaneously. Accordingly the criteria (1), there will not be the oscillation movement in the air gap at the low and the middle frequencies, so, up to the ultimate air oscillation frequency in the gap, $f_{ult.a.}$, the sound insulation on the direct way will contain the sum of insulation by the model "a" or "b" (depending from the wave coincidence frequency for the several layers) and the insulation by the model "c" in figure 3, formula (10):

$$R_{\text{I}}^{\text{A}} = R_{\text{M.A.L.}} + R_a; \text{[dB]}; \qquad (10)$$

where $R_{M.A.L.}$ – is the sound insulation value by equation (8) or (9), [dB], and that, only the mass the most thick layer is taken into consideration due to the instantaneity of the movement transmittance through the all layers; R_a – is the sound insulation by the formula (11), [dB].

$$R_a = 20\lg\left|1 - \left(\frac{f}{f_0}\right)^2\right|, \text{[dB]}; \qquad (11)$$

where f_0 – is the free oscillation frequency of the system, [Hz], by equation (12):

$$f_0 = \frac{60}{\sqrt{a}} \cdot \sqrt{\frac{m_1+m_2}{m_1 \cdot m_2}}; \ \text{[Hz]}; \qquad (12)$$

where a – is the width of an air gap, [m]; m_1 and m_2 – are the surface densities of the first and the second layers respectively.

At the range of $f > f_{ult.a.}$ the oscillation movement in an air gap begins and the model "c" fall into two sequentially working models "a" or "b" depending of the coincidence frequency value of the layers. Thereafter, the equation (13) will be applied at the conveniently second frequency range of the path "A":

$$R_{\text{II}}^{\text{A}} = R_{\text{M.A.L.}}^1 + R_{\text{M.A.L.}}^2; \text{[dB]}; \qquad (13)$$

where $R^1_{M.A.L.}$ and $R^2_{M.A.L.}$ – are the sound insulations for the first and for the second layers respectively, which are calculated by the formula (8) or (9).

Here, also, there will be the lowering of insulation because of the wave resonances in the air gap [20]. These resonances performing lays beyond the framework of this issue. The figure 4 depicts the conventionally insulation curve by the way "A", that is marked by figure "2"; and the plot of the resonance beginning, which is written by figure "3".

The graphs of insulation by the paths "B" and "C" can be obtained on the base of concentrated parameters models application with the usage of transmittance and reflection coefficients at the junctions of considering constructions, but the engineer design permits to take into account the influence of indirect sound ways propagation only through the drawing of additional insulation curve for the insulation of construction layer by the mass action law formula. This additional insulation

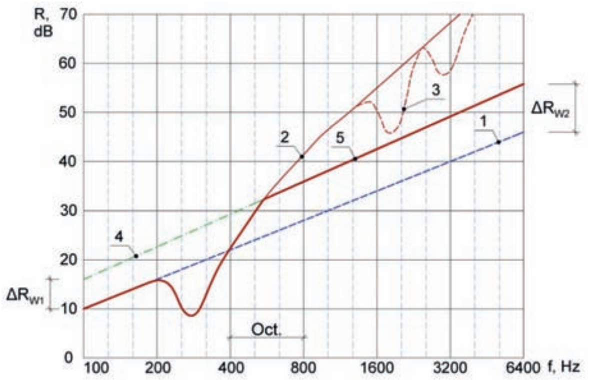


Figure 4. The sound insulation plot of insulation spectrum for the double layer envelope: 1 – is the graph by the mass action law formula (without taking into consideration the wave coincidence phenomenon); 2 – is the curve by the direct sound way propagation; 3 – is the direct way curve segment with insulation lowering due to the resonances; 4 – is the line of the additional insulation to the insulation of one layer defined by the mass action law formula; 5 – is the compound calculation curve

appears due to the losses of oscillation energy in partition's construction layers at the points of their connection with the laterally adjoining walls and slabs, the line 4, figure 4.

The additional insulation value varies from 6 to 12 [dB], the line 4, in the case of tight connections between the walls and slabs, which except hinges and resilient pads.

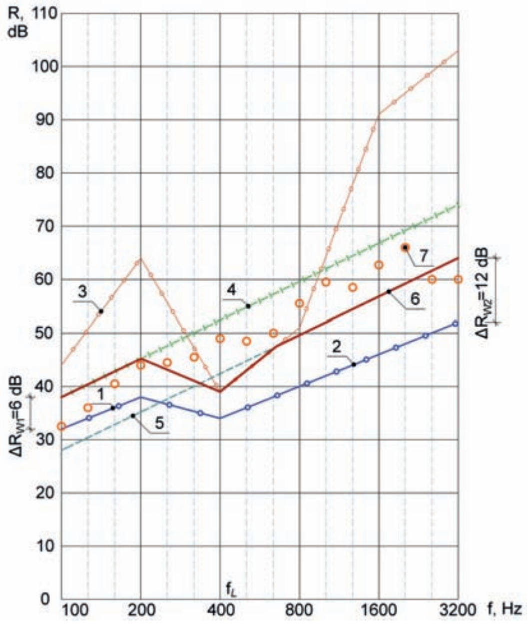
The resultant sound insulation plot is defined by that way, where the maximal sound transmittance is possible, like the compound curve "5" at the figure 4.

3. RESULTS AND DISCUSSION

For an instance, let's graph the insulation curve for the double layered inter-flat separate wall from the gypsum concrete, which is belonged to the typical design of a large-panel building by the Soviet

Table 1. The calculation of double-layered partition's insulationby the way of sound propagation "A" for the example above

Material	Gypsum concrete					
Layer thickness, h, (m)	0,08					
Width of the air gap, a, (m)	0,04					
Surface density, m, (kg·m^{-2})	96					
Current frequency, f, (Hz)	100	200	400	800	1600	3200
Density, ρ, (kg·m^{-3})	1200					
Elasticity modulus, E, (N·m^{-2})	$7 \cdot 10^{9}$					
Dilatational waves velocity, $c_{dil.}$, (m·s^{-1})	2465					
Limiting frequency, f_{L}., (Hz)	326					
Ultimate frequency for the wall material, $f_{ult.w}$, (Hz)	5135					
$R_{M.A.L.1}$, (Hz)	32	38				
$R_{M.A.L.2}$, (Hz)			34	40	46	52
Ultimate frequency for the air gap, $f_{ult.a}$, (Hz)	1417					
Sound insulation, R_{a}, (Hz)	13	26	39	51	63	75
Free vibration frequency, f_{0}, (Hz)	43					
Sound insulation, R^{A}_{I} , (Hz)	44	64	39	51		
Sound insulation, R^{A}_{II} , (Hz)					91	103



<u>Figure 5</u>. The sound insulation plot of insulation spectrum for the double inter-flat wall from gypsum concrete with the layer thickness of 80 mm and air gap of 40 mm: 1 – is the graph by the mass action law formula (8) for one layer's insulation up to the limit frequency; 2 – is the graph by the mass action law formula (9) for one layer's insulation after the limit frequency; 3 – is the direct way insulation curve; 4 – is the graph of additional insulation to the graph of one layer insulation by the mass action law before the limit frequency; 5 – is the graph of additional insulation to the graph of one layer insulation by the mass action law after the limit frequency; 6 – is the resultant curve; 7 – the field measured data

series 12335, [21]. The scheme of construction is similar to figure 2, it has the layer's thickness, $h_1 = h_2 = 80$ *mm*, and the air gap width, $a = 40$ *mm*. The main design parameters and computation results are represented in table 1, the graphs are shown in the figure 5.

The obtained compound curve «6», figure 5, doesn't entirely match with the curve of the field measurements «7», but the same time, it's insulation values lay rather close. The absence of full result coincidence of the given method with the experiment, can be explained by the number of factors, like unknown accurate information on the light-weight concrete mark, on conditions of fixing and measurement. Nevertheless, the gained in this and in another ones calculations results can witness about the theoretically correct calculation performing and about the verity of posing a task for application the acoustic models with the discrete parameters in case of double layer enclosures.

4. CONCLUSIONS

Finally, the following conclusions can be done:

1. It is necessary to take into consideration the direct and indirect ways of sound propagation in the process of calculation of the sound insulation for the double layered partitions.
2. While being treated with the directly air-born sound propagation calculation through the double layered enclosure, the two diapasons at the graph can be derived. They are: the frequency spectrum part, where the insulation is defined simultaneously by the structure's surface weight and by the dump and elastic qualities of the air; and the next one, where the insulation computed by the "Mass Action Law" in the frequency range above the ultimate frequency at the air gap for two layers summarily.
3. The indirect way of sound propagation through the adjoining constructions at the engineer calculation can be taken into account by the drawing line of additional insulation to the graph of the one of the layer's insulation, obtained by the "Mass Action Law".
4. The application of the described above engineer method of the sound insulation's calculation with the usage of the models with the concentrated models approximately allows to find the sound insulation values for massive double layered building partitions across the entire standard frequency range.

It should be pointed out, that the represented calculation method need a further theoretical improvement and an experimental approbation.

REFERENCES

1. **Schelokov Y.A.** Universal'naja formula rascheta zvukoizoljacii odnoslojnyh pregrad [Universal formula of calculation of sound insulation of single-layer barriers]. // Noise Theory and Practice, 2016, pp. 2–7 (in Russian).
2. **Zdražilova N., Donova D., Skotnicova I**. 2016 Analysis of Predictive Calculation Methods of Airborne Sound Insulation. // Applied Mechanics and Materials, 2016, Vol. 835, pp. 573–578.
3. **Neubauer R.O., Kang J.** Airborne sound insulation in terms of a loudness model. // Applied Acoustics, 2014, Vol. 85, pp. 34–45.
4. **Ye Jun**. Applying Immune Algorithems to the Calculation of Sound Insulation of Walls. // Applied Mechanics and Materials, 2014. Vols. 584–586, pp. 1853–1857.
5. **Rodríguez-Molares A.** A new method for auralisation of airborne sound insulation. // Applied Acoustics, 2013, Vol. 74, Issue 1, pp. 116–121.
6. **Huang X., Yang Z., Yang Y.** Prediction on Sound Insulation to a Single-Leaf Wall. // Advanced Materials Research, 2012, Vols. 594–597, pp. 2824–2827.
7. **Zakharov A.V.** conditions of continuity and the conservation laws of mechanics in noize passage's problems. // J. Scientific Review, 2016, Vol. 1.
8. **Zakharov A.V.** Revisiting the dependence of sound transmission on the angle of incidence at the interface between media or massive layer. // Journal of Industrial Pollution Control, 2017, Vol. 33, Issue 1, pp. 878–882.
9. **Zakharov A.V.** Obespechenie uslovij nerazryvnosti pri kosom prohozhdenii zvuka cherez massivnuju plastinu [Providing continuity conditions for oblique sound transmission through a massive plate]. // Innovacii i investicii, 2018, Vol. 12, pp. 163–166 (in Russian).
10. **Zakharov A.V.** Diskretnye modeli prohozhdenija voln pri raschetah zvukoizoljacii v zdanijah [Discrete models of passage of waves for calculation of sound insulation in buildings]. // Industrial and Civil Engineering, 2014, Vol. 11, pp. 50–53 (in Russian).
11. **Zakharov A.V.** The calculation of sound insulation of homogeneous enclosing structures. // The 3rd Nat. Conf. on the Noise Abatement. The reports (Varna: 27–29.10.1973). 1973, Sofia, pp. 316.
12. **Zakharov A.** About some misunderstandings in the modern theory of the sound isolation and discrete models of sound transmission. // Applied Mechanics and Materials, 2013, Vol. 467, pp. 361.
13. **Zakharov A.V.** 2018 Discrete models upon calculation of soundproofing by solid plate. // International Journal of Pure and Applied Mathematics, 2018, Vol. 119, Issue 10, Special Issue C, pp. 439–443.
14. **Saltykov I.P.** An engineering estimation method of the sound insulation of massive partitions on the base of design model with lumped parameters. // IOP Conference Series: Materials Science and Engineering, 2020, Vol. 753, 032046.
15. **Zakharov A.V., Saltykov I.P.** The third frequency range of the sound insulation plot of the single-layer partitions. // IOP Conference Series: Materials Science and Engineering, 2020, Vol. 753, 032064.
16. **Saltykov I.P.** Sravnenie rezul'tatov raschjota zvukoizoljacii odnoslojnyh peregorodok na osnove modeli s sosredotochennymi parametrami s rezul'tatami tradicionnyh metodov rascheta [The comparison of sound insulation calculations results for single-layer partitions, which are based on concentrate parameters model, with the results of conventional calculation methods]. // Innovacii i investicii, 2020, Vol. 2, pp. 173–180 (in Russian).
17. **Saltykov I.P.** Raschet zvukoizoljacii tonkih peregorodok na osnove modeli s sosredotochennymi parametrami [Sound insulation design of the thin partitions on the base of concentrated parameters model].

// Vestnik MGSU, 2020, Vol. 15, Issue 3, pp. 353–367 (in Russian).

18. **Zaborov V.I.** Teorija zvukoizoljacii ograzhdajushhih konstrukcij [The Theory of Sound Insulation of Enclosing Structures]. Moscow, Construction Literature Publishing, 1969, 186 pages (in Russian).
19. **Kl'ukin I.N.** Bor'ba s shumom i zvukovoj vibraciej na sudah [The Noise and Sound Vibration Abatement on the Ships]. Leningrad, Sudostroyeniye Publishing, 1971, 416 pages (in Russian).
20. **Glushkov E., Glushkova N., Eremin A., Lammering R.** Trapped modes and resonance wave transmission in a plate with a system of notches. // Journal of Sound and Vibration, 2018, Vol. 412, pp. 360–371.
21. **Nikol'skiy V.N., Zaborov V.I.** Zvukoizoljacija krupnopanel'nyh zdanij [The Sound Insulation of Large Panel Buildings]. Moscow, Construction Literature Publishing, 1964, 242 pages (in Russian).

СПИСОК ЛИТЕРАТУРЫ

1. **Щелоков Ю.А.** Универсальная формула расчета звукоизоляции однослойных преград. // NOISE Theory and Practice, 2016, с. 2–7.
2. **Zdražilova N., Donova D., Skotnicova I.** 2016 Analysis of Predictive Calculation Methods of Airborne Sound Insulation. // Applied Mechanics and Materials, 2016, Vol. 835, pp. 573–578.
3. **Neubauer R.O., Kang J.** Airborne sound insulation in terms of a loudness model. // Applied Acoustics, 2014, Vol. 85, pp. 34–45.
4. **Ye Jun.** Applying Immune Algorithems to the Calculation of Sound Insulation of Walls. // Applied Mechanics and Materials, 2014. Vols. 584–586, pp. 1853–1857.
5. **Rodríguez-Molares A.** A new method for auralisation of airborne sound insulation. // Applied Acoustics, 2013, Vol. 74, Issue 1, pp. 116–121.
6. **Huang X., Yang Z., Yang Y.** Prediction on Sound Insulation to a Single-Leaf Wall. // Advanced Materials Research, 2012, Vols. 594–597, pp. 2824–2827.
7. **Zakharov A.V.** conditions of continuity and the conservation laws of mechanics in noize passage's problems. // J. Scientific Review, 2016, Vol. 1.
8. **Zakharov A.V.** Revisiting the dependence of sound transmission on the angle of incidence at the interface between media or massive layer. // Journal of Industrial Pollution Control, 2017, Vol. 33, Issue 1, pp. 878–882.
9. **Захаров А.В.** Обеспечение условий неразрывности при косом прохождении звука через массивную пластину. // Инновации и инвестиции, 2018, №6, с. 61–66.
10. **Захаров А.В**. Дискретные модели прохождения волн при расчетах звукоизоляции в зданиях. // Промышленное и гражданское строительство, 2012, №12, с. 20–22.
10. **Zakharov A.V.** Diskretnye modeli prohozhdenija voln pri raschetah zvukoizoljacii v zdanijah [Discrete models of passage of waves for calculation of sound insulation in buildings]. // Industrial and Civil Engineering, 2014, Vol. 11, pp. 50–53 (in Russian).
11. **Zakharov A.V.** The calculation of sound insulation of homogeneous enclosing structures. // The 3rd Nat. Conf. on the Noise Abatement. The reports (Varna: 27–29.10.1973). 1973, Sofia, pp. 316.
12. **Zakharov A**. About some misunderstandings in the modern theory of the sound isolation and discrete models of sound transmission. // Applied Mechanics and Materials, 2013, Vol. 467, pp. 361.
13. **Zakharov A.V.** Discrete models upon calculation of soundproofing by solid plate. // International Journal of Pure and Applied Mathematics, 2018, Vol. 119, Issue 10, Special Issue C, pp. 439–443.
14. **Saltykov I.P.** An engineering estimation method of the sound insulation of massive partitions on the base of design model with lumped parameters. // IOP Conference Series: Materials Science and Engineering, 2020, Vol. 753, 032046.

15. **Zakharov A.V., Saltykov I.P.** The third frequency range of the sound insulation plot of the single-layer partitions. // IOP Conference Series: Materials Science and Engineering, 2020, Vol. 753, 032064.
16. **Салтыков И.П.** Сравнение результатов расчёта звукоизоляции однослойных перегородок на основе модели с сосредоточенными параметрами с результатами традиционных методов расчета. // Инновации и инвестиции, 2020, №2, с. 173–180.
17. **Салтыков И.П.** Расчет звукоизоляции тонких перегородок на основе модели с сосредоточенными параметрами. // Вестник МГСУ, 2020, том 15, №3, с. 353–367.
18. **Заборов В.И.** Теория звукоизоляции ограждающих конструкций. – М.: Стройиздат, 1969. – 185 с.
19. **Клюкин И.Н.** Борьба с шумом и звуковой вибрацией на судах. – Л.: Судостроение, 1971. – 416 с.
20. **Glushkov E., Glushkova N., Eremin A., Lammering R.** Trapped modes and resonance wave transmission in a plate with a system of notches. // Journal of Sound and Vibration, 2018, Vol. 412, pp. 360–371.
21. **Никольский В.Н., Заборов В.И.** Звукоизоляция крупнопанельных зданий. – М.: Стройиздат, 1964. – 242 с.

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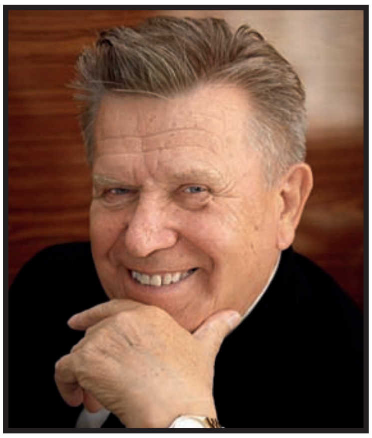

УШЕЛ ИЗ ЖИЗНИ ВИТАЛИЙ ИВАНОВИЧ СОЛОМИН

26 апреля 2020 года ушел из жизни член редакционного совета международного научного журнала “International Journal for Computational Civil and Structural Engineering”, академик Российской академии архитектуры и строительных наук, профессор, доктор технических наук Виталий Иванович Соломин.

Трудовая и творческая деятельность В.И. Соломина на протяжении более чем семи десятилетий – достойный пример для подражания молодому поколению, воспитанию которого он всегда уделял и уделяет большое внимание.

Мы знаем Виталия Ивановича как крупного, признанного в России и за рубежом ученого в области строительной механики, получившего выдающиеся результаты, связанные с решением нелинейных задач расчета и оптимального проектирования фундаментных конструкций и их оснований, основателя и руководителя крупной научной школы, работа которой традиционно была направлена на совершенствование методов расчета и принципов конструирования фундаментных конструкций, опытного организатора науки, образования и просветительской деятельности.

Профессиональная деятельность В.И. Соломина была неоднократно отмечена высокими государственными наградами и почетными званиями, в числе которых орден «Знак Почета», нагрудный знак Министерства высшего образования СССР «За отличные успехи в работе», медаль «50 лет Победы в Великой Отечественной войне», звания Лауреат Государственной премии СССР за заслуги в области науки и техники, Почетный строитель России, Заслуженный деятель науки и техники РСФСР, Почетный гражданин г. Челябинска и другие.

Светлая память о Виталии Ивановиче, выдающимся учёном и руководителе, навсегда сохранится в памяти коллег и учеников.

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УШЕЛ ИЗ ЖИЗНИ ВЛАДИМИР ГЕОРГИЕВИЧ БЕЛЬСКИЙ

В октябре этого года после непродолжительной болезни на 63-м году жизни умер заместитель главного редактора журнала Владимир Георгиевич Бельский, признанный специалист в области разработки и внедрения высокопроизводительных численных методов для расчетов и оптимального проектирования строительных конструкций и сооружений.

Владимир Георгиевич родился в 1958 году в Киеве. По окончании обучения в Московском государственном строительном университете (МГСУ) по специальности «теория сооружений», Владимир Георгиевич преподавал и работал над кандидатской диссертацией на кафедре прикладной математики МГСУ. После защиты кандидатской диссертации продолжил свою научную деятельность в Центральном научно-исследовательском институте строительных конструкций (ЦНИИСК им. В.А. Кучеренко), где успешно возглавлял лабораторию оптимизации строительных конструкций отделения теории сооружений и численных методов.

В 1993 году В.Г. Бельский принял приглашение на проведение научных исследований в Тройском политехническом институте, США (Rensselaer Polytechnic Institute (RPI) in Troy, New York). Последние 24 года он работал в корпорации HKS-Abaqus, США (теперь Dassault Systèmes Simulia Abaqus) – разработчике завоевавшего признание во многих странах мира, в том числе в России, программного комплекса Simulia Abaqus для расчета механических систем, включая уникальные здания и сооружения. В этом коллективе он возглавлял департамент разработки программного обеспечения для решения систем алгебраических уравнений и проблемы собственных значений (решателей) большой и сверхбольшой размерности для численного расчета сооружений на прочность, устойчивость и динамические воздействия. По мнению руководителей корпорации и коллег В.Г. Бельский, благодаря своей высокой эрудиции в математике и механике, а также лидерским качествам, оказал существенное, последовательное, новаторское влияние на технологические решения при разработке программного обеспечения для компьютерного моделирования конструкций и сооружений. При этом, большое внимание он уделял решению практических прикладных задач.

Владимира Георгиевича отличали незаурядные способности, высокие человеческие качества, целеустремленность, трудолюбие, оптимизм, любовь к своей семье, доброжелательность, тонкое чувство юмора.

Светлая память о Владимире Георгиевиче Бельском будет вечно жить в сердцах и памяти тех, кто его знал.

Выражаем искренние соболезнования родным, близким и коллегам в связи с невосполнимой утратой.

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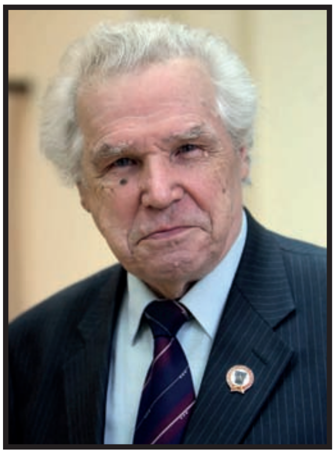

УШЕЛ ИЗ ЖИЗНИ ЮРИЙ МИХАЙЛОВИЧ БАЖЕНОВ

13 декабря 2020 года ушёл из жизни Юрий Михайлович Баженов – выдающийся учёный-материаловед, академик РААСН и РИА, заслуженный деятель науки Российской Федерации, Почётный строитель России, Москвы и Московской области, строитель Байконура, президент Международной ассоциации учёных и специалистов в области строительного материаловедения, почётный профессор Белгородского технологического университета им. В.Г. Шухова, почётный доктор Веймарской высшей школы по архитектуре и строительству (Германия), председатель специализированного диссертационного совета НИУ МГСУ по строительным материалам, изделиям и строительному материаловедению, член редколлегий ведущих научных журналов по строительству и строительному материаловедению (в том числе член Редакционного Совета международного научного журнала “International Journal for Computational Civil and Structural Engineering”), профессор, доктор технических наук, многолетний заведующий кафедрой «Технологии вяжущих веществ и бетонов».

Юрий Михайлович Баженов – основатель научной школы современных проблем бетоноведения и технологии строительных композитов гидратационного твердения, в том числе на вяжущих веществах низкой водопотребности и с использованием гелиотехнологии в условиях сухого и жаркого климата, значителен его вклад в создание новых видов бетонов различного назначения, обладающих уникальными эксплуатационными показателями, в развитие теории их проектирования и прогнозирования свойств, в разработку современных методов испытаний строительных материалов.

Ю.М. Баженов родился 25 марта 2020 года в Москве, в семье военнослужащего. В 1954 году окончил Инженерно-строительный факультет Военно-инженерной академии им. В.В. Куйбышева и был направлен служить на Северный Военно-морской Флот, где строил оборонные объекты для укрепления безопасности нашей Родины. В 1960–1970 годы служил в Военно-инженерной академии им. В.В. Куйбышева на различных научных и педагогических должностях. В 1960 году защитил диссертацию на соискание учёной степени кандидата, а в 1965 году – доктора технических наук. С 1975 года Ю.М. Баженов заведовал кафедрой «Технологии вяжущих веществ и бетонов» МИСИ им. В.В. Куйбышева – НИУ МГСУ.

Работая в Московском государственном строительном университете, Ю.М. Баженов проводил большую работу по подготовке профессиональных, научных и педагогических кадров, высококвалифицированных специалистов, которые успешно работают во многих ведущих организациях строительной отрасли в различных регионах России, бывших союзных республиках и в ряде зарубежных стран. Он активно участвовал в становлении системы послевузовского профессионального образования строительных кадров. Им подготовлено 12 докторов и 65 кандидатов технических наук. Результаты научно-исследовательских наук, выполненных под руководством Ю.М. Баженова, широко внедрены в современном строительстве и получили признание на многих международных и российских научных конгрессах и конференциях.

За время работы в МИСИ-МГСУ Юрием Михайловичем опубликованы 250 фундаментальных научных трудов, 60 изобретений, 35 монографий, учебников и учебных пособий, которые широко используются как в учебном процессе многих российских строительных вузов и строительных вузов ближнего зарубежья, так и в среде специалистов строительной индустрии.

За свой добросовестный и плодотворный труд на благо строительной науки и образования Ю.М. Баженов был награждён орденами «Знак Почёта» и «Инженерная слава», одиннадцатью медалями, многими почётными грамотами и знаками, стал лауреатом премий Совета Министров СССР и Правительства Российской Федерации.

Светлая память о Юрии Михайловиче Баженове, выдающимся учёном, талантливом организаторе и руководителе, благожелательном, внимательном и чутком к проблемам других человеке навсегда сохранится в памяти коллег и многочисленных учеников.

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