2019. 15(3). 171–181

СТРОИТЕЛЬНАЯ МЕХАНИКА ИНЖЕНЕРНЫХ КОНСТРУКЦИЙ И СООРУЖЕНИЙ

STRUCTURAL MECHANICS OF ENGINEERING CONSTRUCTIONS AND BUILDINGS

HTTP://JOURNALS.RUDN.RU/STRUCTURAL-MECHANICS

РАСЧЕТ И ПРОЕКТИРОВАНИЕ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ

UDC 624.012
DOI: 10.22363/1815-5235-2019-15-3-171-181

RESEARCH PAPER

Method of full discretization in joint calculation in time of the system “construction – foundation – soil”

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Keywords:
method of full discretization;
creep;
displacements;
deformations;
stresses;
concrete construction;
stress-strain; tank;
history of construction

Article history:
Received: March 20, 2019
Revised: April 22, 2019
Accepted: May 11, 2019

For citation
Ter-Emmanuilyan T.N., Polumordvinov I.O. (2019). Method of full discretization in joint calculation in time of the system “construction – foundation – soil”. *Structural Mechanics of Engineering Constructions and Buildings, 15*(3), 171–181. http://dx.doi.org/10.22363/1815-5235-2019-15-3-171-181

Abstract

Introduction. Prospective transition of CIS to the European design standards in the construction industry requires development of new and modification of known engineering methods for calculation and design of construction. Creation and development of such methods should be based on fundamental research that can become the basis for the development of principally new, innovative technologies.

Methods. The paper consists of basis and practical application of the method of full discretization. This method is a special modification of finite element method for the solving of problems of the creep. Practical application of the method is illustrated with modeling and applied tasks.

Results. The paper presents a joint calculation of the “structure – foundation – soil” system using the example of a reservoir of a modular biological wastewater treatment plant designed for filtration fields in the village of Tasboget, Akmola region, the Republic of Kazakhstan. The full picture of the evolution of the stress-strain state of structures is gained, taking into account the material creep and the history of construction. There is a comparison of result calculations with and without technology of erection of structures.

Introduction

Prospective transition of CIS to the European design standards in the construction industry requires development of new and modification of known engineering methods for calculation and design of construction [1–3].

Creation and development of such methods should be based on fundamental research that can become the basis for the development of principally new, innovative technologies [4].

One of such directions is the further development and perfection of methods of analysis of structures and grounds, more precise estimate of evolution of the deformation stress state (DSS) and the yield of the building foundation in time. It is important to consider inelastic and nonlinear properties of building materials and structures, spatial and temporal in homogeneity, i.e. construction technology and other factors influencing their deformability, strength, durability and stability [5].

The basis for calculating any projected building object is its closed mathematical model, usually represented by systems of differential or integro-differen-

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tial equations with boundary and initial conditions. However, the analytical solution of such systems of equations can be obtained only in special cases for objects with a simple geometric shape with simple boundary and initial conditions. The way out was found by introducing various types of discretization of a continuous problem in which an infinite set of numbers representing the unknown function is replaced by a finite number of unknown parameters. As a result, the system of differential equations for real-world problems tends to turn into large systems of algebraic equations that can be solved only with the help of modern computer technology [6–9].

Method of full discretization (FDM) – special modification of the finite element method (FEM) for the solving of various problems of the elastic creep, offered by N. Ter-Emmanuilyan [10].

FDM – universal, comparatively simple and obvious engineering method being "not step-by-step" in time. It gives an opportunity to determine discrete values of displacements, deformations and stresses in a calculated interval of time. The method is developed both in variant of displacements, and in variant of forces. It can be combined with other engineering numerical methods, such as a method of boundary elements, a method of finite differences and others. [11].

The FDM allows to take into account: a heterogeneous creep and ageing of materials of any constructions and foundation soils; physical and geometrical nonlinearity; plasticity; anisotropy; different modular elastic creep; influence of temperature; presence stressed enforcement and normal armatures in ferro-concrete; discrete diagrams of erection of constructions (increase or reduction of volumes, change of operational loadings, etc.) [12].

The method is applied at the decision of a wide class of engineering problems of a linear and nonlinear elastic creep. For example: plane problems; axisymmetric; three-dimensional; single-layered and multilayered plates and envelopes; bar and thin-walled systems; stability of plates and bars; contact problems; thermoelastic creep problems; a short-time high-temperature creep of metals, etc.

The mathematical justification of a FDM as a version of a method of weighted residuals and also approximation and discretization error in numerical solutions is considered. The appropriate algorithms of the solutions of linear and nonlinear problems of elasticity, elastic creep and plasticity are constructed. The package of application software for engineers and researchers is developed.

The wide class of modelling and applied engineering problems are solved: calculation of evolution of stress-deformation state in the system "tunnel lining – rock"; reinforced concrete pipe – backfilling; a heterogeneous thick-walled shell with steel facing at loading and unloading; research of evolution of stress-deformation state of the vertical supported shaft at drivage with the preset speed; calculation in time reinforced concrete wall panels with holes; calculation of multilayered plates in view of a creep of some layers; buckling of flexible plates; buckling of a rod and cylindrical bend of a plate with initial camber; research on model Shenly at conservative and following loadings; calculation of prestressed ferroconcrete rods; combined calculations of growing buildings and constructions and their bases [13]:

– an evolution of stress-deformation state of a foundation ferroconcrete plate on a soil base;

– a problem about of influence of non-simultaneity of erection of buildings on evolution of the stress-deformation state in constructions and basis at the constrained building of city territories;

– calculations of the box-shaped substructure and the basis of high-altitude television tower on Kok-Tyube mountain near Almaty city in three variants of statement of a task: plane, quasi-spatial and spatial;

– calculation of a road embankment and its basis;

– calculation in time four-level a ferro-concrete construction and its basis, etc.

1. Bases of the method

Stress-deformation state (SDS) the elastic creep, homogeneous and isotropic body loaded in the age of $\tau = \tau_1$ at small deformations in static problems completely is determined, if all are known 15 components of a vector:

$$\bar{f}\left(x^i,t,\tau\right)=\left[\bar{u}^T\left(x^i,t,\tau\right)\bar{\varepsilon}^T\left(x^i,t,\tau\right)\bar{\sigma}^T\left(x^i,t,\tau\right)\right],$$
$$\left(i=1,2,3\right),$$

as functions of coordinates and time, satisfying in each point to system of the matrix-vector equations:

$$\begin{pmatrix} -\underline{n}^T & \underline{J} & \underline{0} \\ \underline{0} & \underline{J} & -\underline{L}_t \\ \underline{0} & \underline{0} & \underline{n} \end{pmatrix} \cdot \begin{pmatrix} \bar{u} \\ \bar{\varepsilon} \\ \bar{\sigma} \end{pmatrix} + \begin{pmatrix} \bar{0} \\ \bar{0} \\ \bar{\rho} \end{pmatrix} = \bar{0}. \quad (1)$$

And to boundary conditions in movings on S_1 and in superficial forces on S_2. In system (1) $\underline{n}$ (3×6) – a matrix of linear differential operators on coordinates; $\bar{\rho}=\left[XYZ\right]^T$ – a vector of volumetric forces; $\underline{n}_s$ – a matrix directing cosines an external normal to a surface, but with replacement of operators of differentiation $\partial/\partial x^i$,... on cosines $\cos\left(\bar{\nu},x^i\right)$,...; $\underline{J}$ –

a unit matrix; $\underset{6\times 6}{\underline{L}_t}$ – a matrix of integro-differentual operators of an elastic creep with 12 nonzero elements L_{ij} from which $\underline{L}_{t11}$ has the following kind:

$$L_{t11}=\frac{1}{E(\tau_1)}+C(t,\tau_1)+\int_{\tau_1}^{t}\left[\frac{1}{E(\tau)}+C(t,\tau)\right]\frac{d\ldots}{d\tau}=$$

$$=\delta(t,\tau_1)+\int_{\tau_1}^{t}\delta(t,\tau)\frac{d\ldots}{d\tau}. \quad (2)$$

Matrix $\underline{L}_t$ in usual designations is constructed on the basis of the equations of a condition for linear three-dimensional elastocreep the bodies, received by N.H. Arutjunjan [14].

For the decision of system of the equations (1) the numerical method of the decision based on full, existential digitization (FDM) was offered [10].

Digitization of objects in FDM on geometry is carried out as well as in FEM at the decision elastic and elastoplastic problems.

The limited time piece (day, years) digitize p time points.

For uniaxial the discrete form of the equation of a condition looks like the intense condition:

$$\varepsilon_i=\sigma_i\delta_{i1}+\sum_{j=2}^{i}\int_{t_{j-1}}^{t_j}\frac{d\sigma(\tau)}{d\tau}\delta_i(\tau)\,d\tau,$$

$$(i=1,2,3,\ldots,p),\ (j=2,3,\ldots,p). \quad (3)$$

In (3) integral it is broken for the sum of integrals, the derivative is replaced differential.

The formula (3), after introduction of matrix restrictions, gets a kind conterminous under the form with Hooke's law:

$$\bar{\varepsilon}=\underline{E}^{-1}\bar{\sigma}, \quad (4)$$

where $\bar{\varepsilon}$ and $\bar{\sigma}$ – vectors of discrete values.

The return square-bottom triangular matrix of matrix "module" $\underline{E}$ describing elasticity, hereditary creep and ageing of a material:

$$\underset{p\times p}{\underline{E}^{-1}}=\begin{pmatrix}\delta_{11} & 0 & \ldots & 0\\ \delta_{21}-\tilde{\delta}_{22} & \tilde{\delta}_{22} & \ldots & 0\\ \ldots & \ldots & \ldots & \ldots\\ \delta_{p1}-\tilde{\delta}_{p2} & \tilde{\delta}_{p2}-\tilde{\delta}_{p3} & \ldots & \tilde{\delta}_{pp}\end{pmatrix}, \quad (5)$$

in which sizes $\tilde{\delta}_{ik}$ are calculated under the formula

$$\tilde{\delta}_{ik}=\frac{1}{t_k-t_{k-1}}\int_{t_{k-1}}^{t_k}\delta_i(\tau)\,d\tau, \quad (6)$$

or, is simplified,

$$\tilde{\delta}_{ik}=\frac{\delta_{ik}+\delta_{i,k-1}}{2}. \quad (7)$$

Thus

$$\delta(t,\tau)=\frac{1}{E(\tau)}+C(t,\tau). \quad (8)$$

Generally triaxial the SDS, from six scalar integrated equations of a condition making the second group of the matrix equations (1) it is received, after sampling, the system of the algebraic equations having the form of generalized Hooke's law:

$$\left.\begin{array}{l}\bar{\varepsilon}_x=\underline{E}^{-1}\bar{\sigma}_x-\underline{\mu}\underline{E}^{-1}\left(\bar{\sigma}_y+\bar{\sigma}_z\right)\\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\\ \bar{\gamma}_{xy}=2\underline{E}^{-1}\left(\underline{J}+\underline{\mu}\right)\bar{\tau}_{xy}\\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\end{array}\right\}, \quad (9)$$

where $\underline{\mu}=\underline{\nu}\ \underline{\Pi}$.

An auxiliary matrix:

$$\underline{\Pi}=\begin{pmatrix}1 & 0 & 0 & 0 & \ldots & 0\\ -1 & 1 & 0 & 0 & \ldots & 0\\ 0 & -1 & 1 & 0 & \ldots & 0\\ 0 & 0 & -1 & 1 & \ldots & 0\\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots\\ 0 & 0 & 0 & 0 & -1 & 1\end{pmatrix}, \quad (10)$$

$\underline{\nu}$ – the bottom triangular matrix generated from sizes ν_{ij}:

$$\nu_{ij}=\begin{cases}\nu(t_i,\tau_j), & (i\le j)\\ 0, & (i<j)\end{cases},\quad \nu(t,\tau)=\frac{\tilde{\varepsilon}(t,\tau)}{\varepsilon_0(\tau)}. \quad (11)$$

At construction of matrixes $\underline{E}$ and $\underline{\mu}$ it is possible to use theories of creep or the data of base experiments. As a result of generalization of physical parities(ratio) of the linear theory of creep and matrix "Hooke's law" (10), the matrix form of the law of a linear elastic creep is received in a general view:

$$\bar{\sigma}_t=\underline{D}_t\bar{\varepsilon}_t, \quad (12)$$

where $\underline{D}_t$ – the generalized matrix of a linear elastic creep having in scalars 6p the order, $\bar{\sigma}_t$ and $\bar{\varepsilon}_t$ – 6p-

dimensional (3p-dimensional in flat problems) on components tensors and to time points of vectors of stresses and deformations.

At a conclusion of the formula calculation of the matrix of rigidity of a final element generalized in time for quasistatic problems of an elastic creep the principle of possible movings Lagrange is used. In result the formula is received:

$$\underline{k}_t^r = \int_V \underline{B}_1^T \underline{D}_t \underline{B}_1 dv, \quad (13)$$

where $\underline{B}_1$ – a matrix of communication of components of movings and deformations in time in *FE*:

$$\bar{\varepsilon}_t^r = \underline{B}_1 \bar{q}_t^r. \quad (14)$$

Looks like a rectangular matrix generally about $6p \times 3np$ (n – number of units in *FE*).

Matrix $\underline{B}_1$ turns out from a usual matrix in way of expansion of each scalar member $B_{k\ell}$ in diagonal blocks – matrixes of the order p with constant diagonal elements $B_{k\ell}$.

The matrix $\underline{k}_t^r$ of rigidity generalized in time elastocreep a final element has the order in p time the greater, than the order $\underline{k}_r$ – matrixes of rigidity of an elastic element due to replacement of scalar elastic constants E and ν bottom triangular matrixes $\underline{E}$ and $\underline{\mu}$ the order p. The generalized matrix of rigidity $\underline{K}_t$ of system elastocreep elements which is square, block, the order, generally, $3Np$ (N – the general (common) number of units of elements of system) further is resulted. For uniformity on properties of an elastic creep of a body, this matrix can be received very simply – as well as $\underline{k}_t^r$ – by expansion of scalars E and ν in matrixes $\underline{E}$ and $\underline{\mu}$ p the order.

At calculation of the designs consisting from non-uniform on properties or age of materials, blocks of matrix $\underline{K}_t$ of system are calculated only by summation on the elements containing units i and j of global numbering of the appropriate members of generalized matrixes of rigidity of final elements:

$$\underline{K}_{tij} = \sum_{r \ni ij} \underline{k}_{tij}^r. \quad (15)$$

Further allowing linear matrix algebraic equation concerning a required vector $\bar{q}_t$ of components of movings in time of all units of system is submitted:

$$\underline{K}_t \cdot \bar{q}_t = \bar{R}_t, \quad (16)$$

where $\underline{K}_t$ – generalized stiffness matrix of system (SMS) in which the kinematic boundary conditions having an opportunity to change in a settlement interval of time are taken into account; $\bar{R}_t$ – a vector of a variable or a constant in time of central loading.

2. Results of numerical modelling

Let us consider joint in time calculation of two-tier reinforced concrete building and its foundation in the spatial formulation in the example of modular station tanks of biological sewage treatment with capacity of 6400 m^3/day designed for filtration fields in the village Tasboget, Akmola Oblast, Kazakhstan (Figure 1).

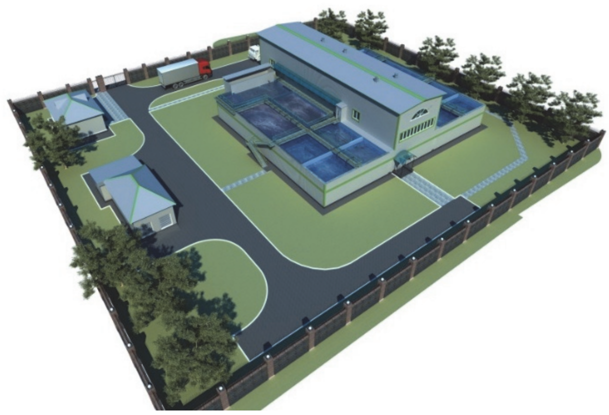


Figure 1. General view of the biological treatment of sewage

The tanks of the modular station are made of concrete B25 with the following mechanical properties: initial modulus is 30 000 MPa, the calculated resistance to axial compression is 14.5 MPa, the calculated resistance to axial tension is 1.0 MPa. There was used the reinforcement armature of Class A-III with mechanical properties: modulus of elasticity is 200 000 MPa, the design resistance is 367.7 MPa.

In building practice erection of any constructions is an example *ph* growing in time. Depending on concrete conditions, process of escalating of viscoelastic bodies can occur both discretely, and is continuous. The account of a time history of development and loading bodies frequently results in qualitative changes in their mechanical behaviour. At designing large ground and underground constructions, it is especial in conditions of city building, performance of stage-by-stage geotechnical calculation, since process of construction and finishing an operation phase is expedient. Thus results of calculations can differ from usual on the order, and sometimes and with change of a mark [15].

The model of concrete with "smeared" reinforcement were used in the calculation of the building to account for the rheological properties of the material of the tanks. In this case, the behaviour of elastic creeping material (concrete or reinforced concrete with “smeared” reinforcement) can be described by equations of the hereditary theory of aging with a measure of creep by S.V. Aleksandrovskiy [16].

$$\delta(t,\tau)=\frac{1}{E}\left(1-e^{-\beta\tau}\right)+\psi(\tau)-$$
$$-\psi(\tau)\frac{e^{\gamma\tau}-A_2}{e^{\gamma\tau}-A_2}+\Delta(\tau)\left[1-e^{-\alpha(1-\tau)}\right],$$

where

$$\Delta(\tau)=C_1-C_3+\frac{A_1-A_3}{\tau},\quad \psi=C_3+\frac{A_3}{\tau},$$

the values for parameters of creep are taken in accordance with recommendations of N.H. Aratyunyan [14]: $\alpha = d^{-1}$, $\beta = 0.206\ d^{-1}$, $\gamma = 0.03\ d^{-1}$, $A_1 = 4.62\cdot10^{-5}\ d/(\text{kgf/cm}^2)$, $A_2 = 1$, $A_3 = 3.416\cdot10^{-5}\ d/(\text{kgf/cm}^2)$, $C_1 = 0.975\cdot10^{-5}\ (\text{kgf/cm}^2)^{-1}$, $C_3 = 0.756\cdot10^{-5}\ (\text{kgf/cm}^2)^{-1}$ are the parameters of creep, E_o=30 000 MPa.

Then we use the measure and kernel of Zh.S. Erzhanov [17] to describe the behaviour of elastic creeping ground:

$$\delta(t,\tau)=\frac{1}{E}\left[1+\frac{\Delta}{\alpha}(t-\tau)^{\alpha}\right]$$

obtained from the difference kernel

$$L(t-\tau)=\Delta(t-\tau)^{\alpha-1},$$

where Δ, α are the creep parameters.

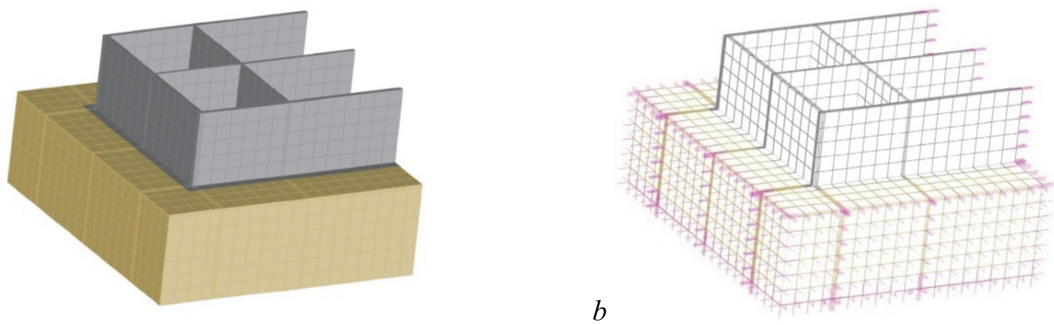
The influence of the weight of a building on the deformation stress state of the soil mass is considered with assumption of smallness of the deformation with respect to the size of the deformed region. The same assumption remains valid when the yield of a building is considered near walled pits, underground structures, natural slopes, etc. The hypothesis about the smallness of the deformation is not applicable only when deformations comparable to the size of the deformable region (i.e. the process of sliding slope, buckling, etc.) are considered [19].

Since the modern theory of creep contains a number of errors [20–23], we correct these errors by selecting coefficients; we perform the adapting of creep parameters for specific structures using experimental data [24].

The analytical model of building is shown in Figure 2, *a*. Due to the presence of symmetry plane, only half of the tank is considered in the calculation.

This design scheme is split into 6212 octanodal prismatic volume elements connected in 7714 nodes. Boundary conditions in the form of rod connections are shown in Figure 2, *b*.

Figure 3 shows the projections of the tank with building axes.

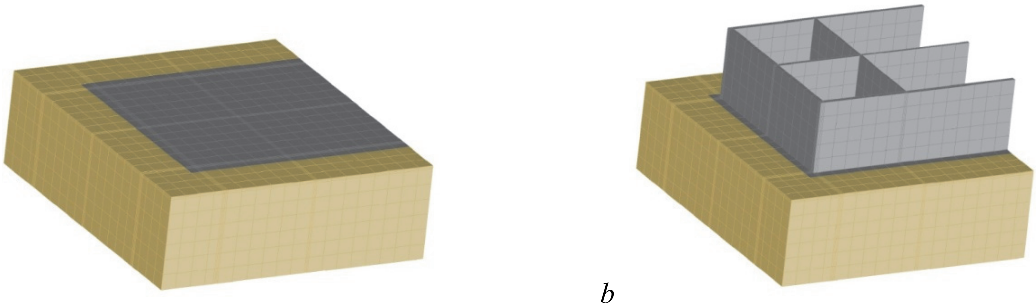


a *b*

Figure 2. Design scheme of the tank

Figure 3. Frontal and upper projections of the tank

Building of the tank is carried out in two stages. The first stage is the concreting of the base plate. The duration of this phase is 30 days (5 time points) (Figure 4, *a*). The own weight of the base plate is taken into account at this stage. The second stage is the concreting of the walls of the tank. The own weight of the base plate and the tank walls is taken into account at this stage. The duration of this stage is 90 days (5 time points) (Figure 4, *b*). In the third stage the tank is filled with water. The own weight of the base plate and the tank walls is taken into account at this stage. Duration of this stage is 480 days (10 time points) (Figure 4, *b*).



a *b*

Figure 4. Stages of construction of building

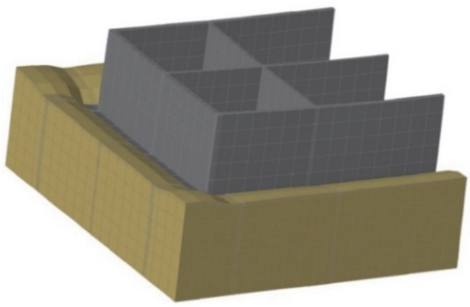


Figure 5. Deformed diagram computational region in 600 days

The timeline for calculations is taken uneven, with increasing intervals to the end of the scale. This makes it possible to estimate the evolution of the deformation stress state of the tank, both during periods of construction and initial operation.

Information about the components of nodal displacements in 7714 nodes for the 20 time points is obtained as a result of the calculations. The components of vectors of deformations and stresses for each time point, at all 6212 finite elements are calculated. Thus, the complete picture of evolution of the displacement vectors, deformations and stresses in space and time is obtained.

Let us consider some typical results of calculations of the change of the deformation stress state of the reservoir in time. Software module in AutoCAD was developed during the study. This module was used for graphical interpretation of the results obtained. The input data for this module are parameters of FEM of the construction model (nodes, elements, supports, loads, stiffness) and the results of solution of the problem MFD for given construction (vectors of displacements, deformations and stresses in each of the time points of the interval).

The figure shows the deformed scheme of computational region (scale deformation increased 30-fold) for the last time point – in 600 days after the construction of buildings.

Figure 6, *a, b, c, d* shows the contours of vertical displacements for $t_4 = 20$, $t_9 = 70$, $t_{14} = 200$, $t_{20} = 600$ days, which illustrate the evolution of vertical displacements.

Isolines of the horizontal components of displacements for time points $t_9 = 70$, $t_{20} = 600$ days are shown in Figure 7 (*a, b*).

Figure 8 shows diagrams of yield of tank elements located along the axis 4, and Figure 9 shows diagrams of yield of tank elements along *C*-axis for four time points corresponding to the four stages of erection: t_4, t_9, t_{14} and t_{20} (respectively curves 1, 2, 3, 4).

Figure 9 shows the displacements (yield) of more typical node that is located at the intersection of the axes *C* and 5 depending on time for the entire range of the study.

Analysis of the solution reveals the significant incremental growth of displacement in time (Figure 10) and deformation (on the example of the vector components of ground deformations in the element number 2451 – Figure 11). Evolution of stress tensor components (on the example of the components of the stress vector in the ground element number 2451 – Figure 12) within each time step virtually are unchanged.

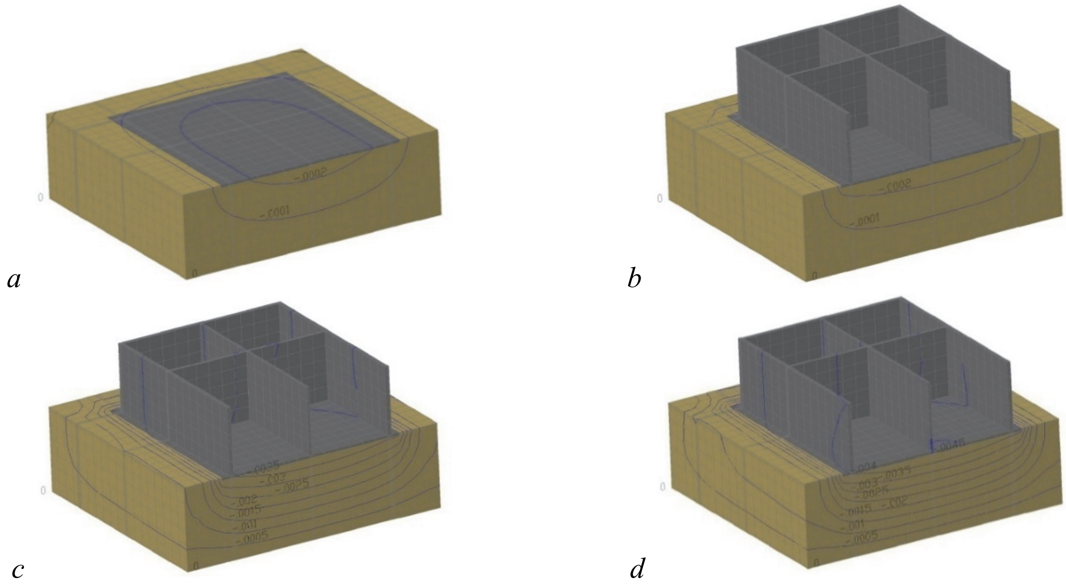


Figure 6. Contours of vertical displacements for times t_4 (*a*), t_9 (*b*), t_{14} (*c*), t_{20} (*d*)

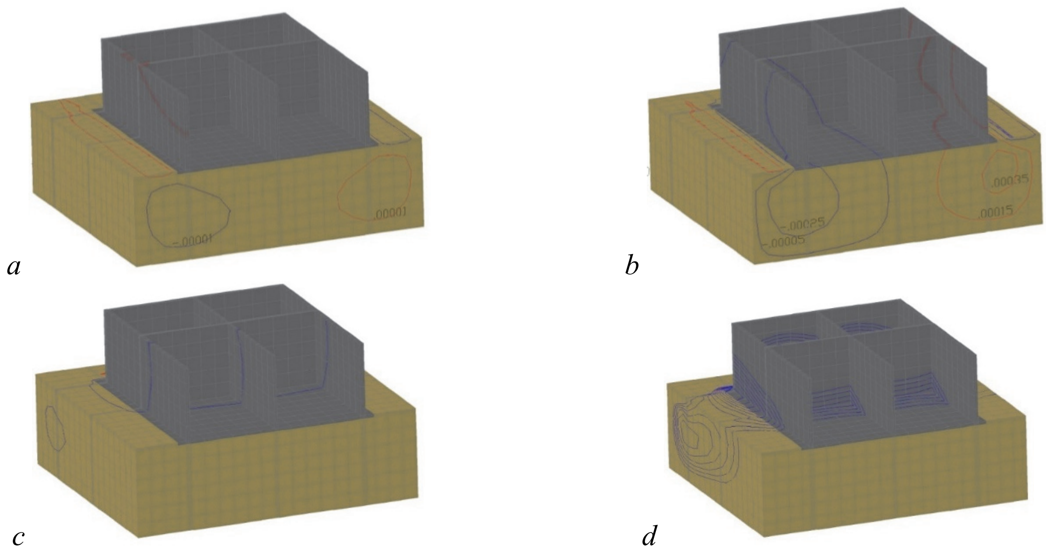


Figure 7. Contours of horizontal components of displacements for times t_9 (*b*), t_{20} (*d*)

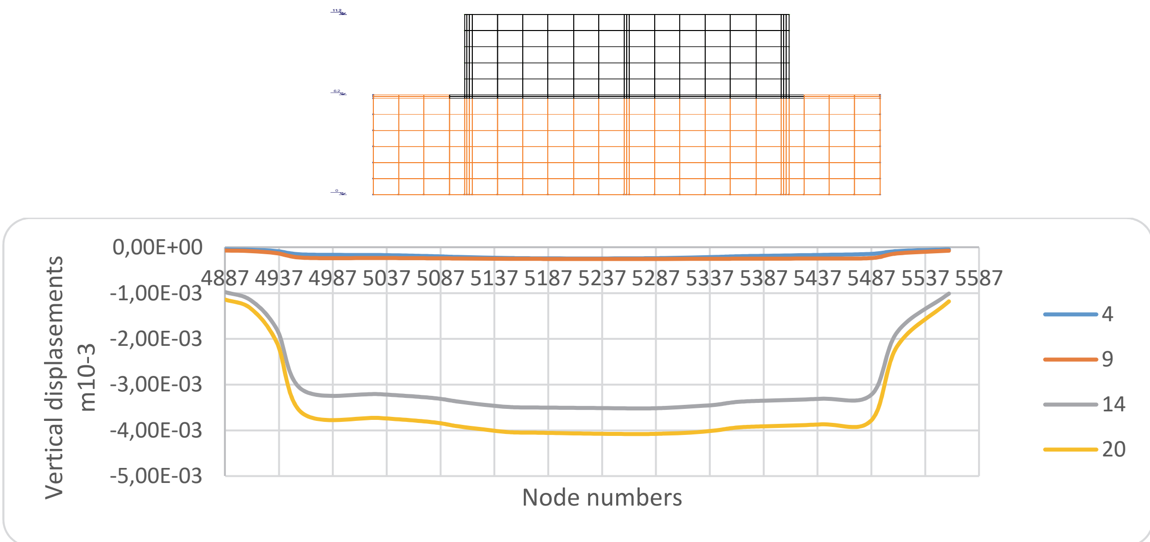
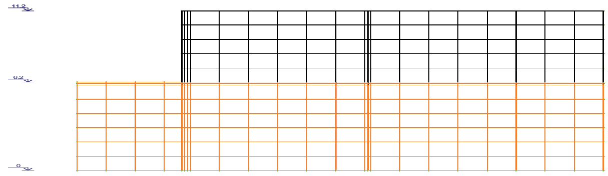


Figure 8. Diagrams of yield of nodes (*m*) along the axis 4. Curves correspond to the times: *1* – t_4; *2* – t_6; *3* – t_{14}; *4* – t_{20}



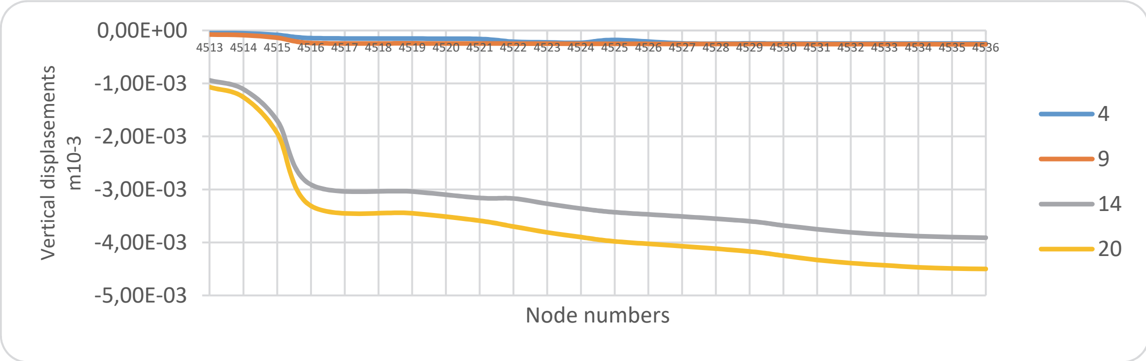


Figure 9. Diagrams of yield (*m*) of nodes along the axis *C*. Curves correspond to the times: *1* – t_4; *2* – t_6; *3* – t_{14}; *4* – t_{20}

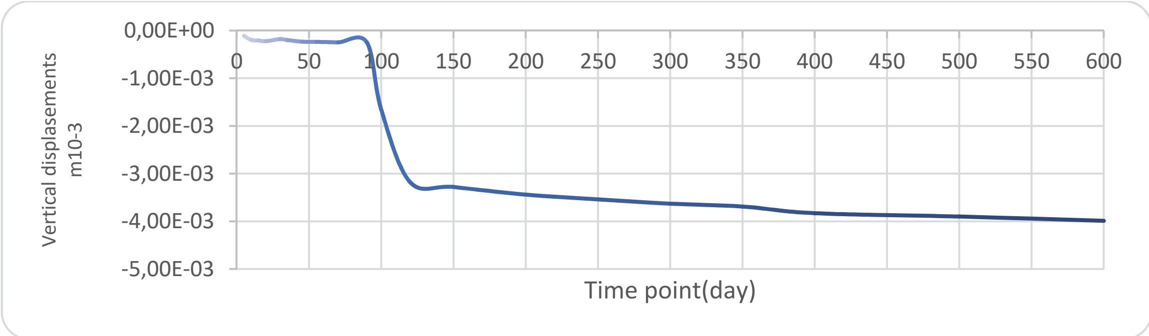


Figure 10. Diagrams of yield (*m*) of element at the intersection of the axes of *C*-5. Curves correspond to times: *1* – t_4; *2* – t_6; *3* – t_{14}; *4* – t_{20}

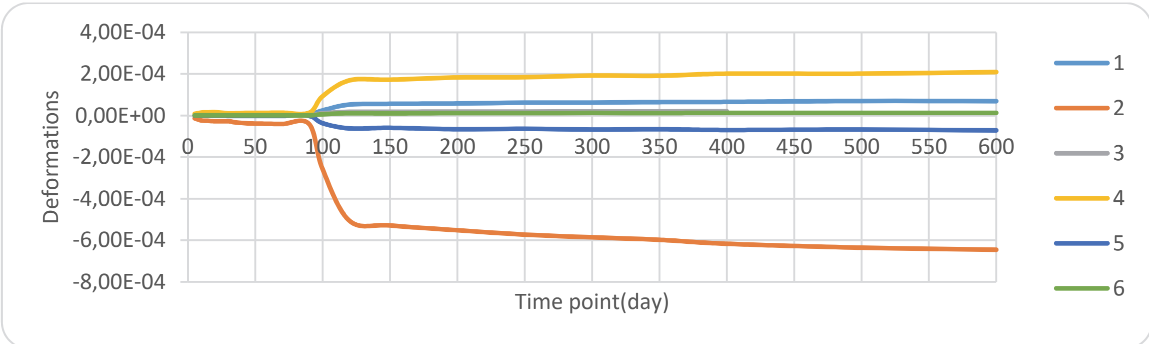


Figure 11. Dependence of the components of vector in the element of deformation of the soil mass number 2451 on time

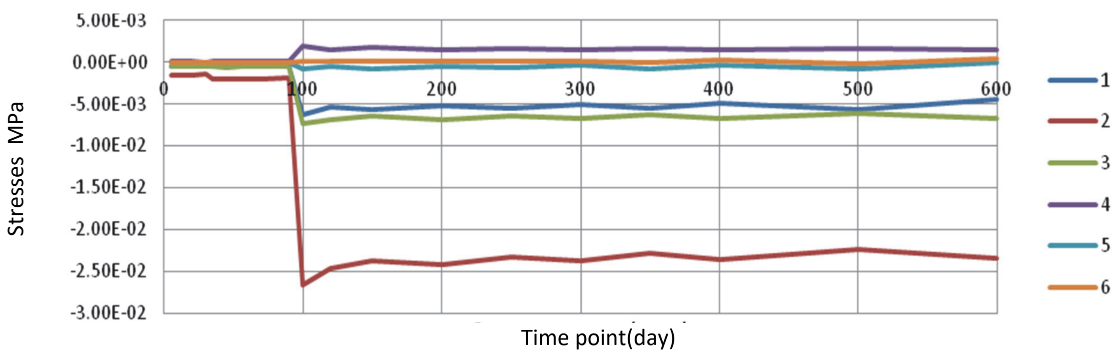


Figure 12. Dependence of the components of the stress vector in the element of the soil mass number 2451 on time

Conclusions

The developed method can be used in calculations and design of large-scale structures in the form of buildings, dams, and other objects taking into account their joint performance with the soil and bedrock, the temporal and spatial inhomogeneity due to creep materials. In addition, the developed software packages are convenient because of their user-friendly interface, advanced automation data input and processing of the results.

Methodology developed in practice and the results obtained allow to predict the change of DSS in time considering construction projects with high accuracy over a long period of operation, even with the possibility of reconstruction. Such consideration can lead to significant changes of DSS (by an order of magnitude and higher) for the entire period of operation.

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НАУЧНАЯ СТАТЬЯ

Метод полной дискретизации в совместном расчете во времени системы «конструкция – фундамент – грунт»

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Ключевые слова:
метод полной дискретизации;
ползучесть;
перемещения;
деформации;
напряжения;
бетонная конструкция;
резервуар;
история строительства

История статьи:
Поступила в редакцию: 20 марта 2019 г.
Доработана: 22 апреля 2019 г.
Принята к публикации: 11 мая 2019 г.

Для цитирования
Ter-Emmanuilyan T.N., Polumordvinov I.O. Method of full discretization in joint calculation in time of the system "construction – foundation – soil" (Метод полной дискретизации в совместном расчете во времени системы «конструкция – фундамент – грунт») // Строительная механика инженерных конструкций и сооружений. 2019. Т. 15. № 3. С. 171–181. http://dx.doi.org/10.22363/1815-5235-2019-15-3-171-181

Аннотация

Цели исследования. Перспективный переход СНГ на европейские стандарты проектирования в строительной отрасли требует разработки новых и модификации известных инженерных методов расчета и проектирования строительства. Создание и развитие таких методов должно основываться на фундаментальных исследованиях, которые могут стать основой для разработки принципиально новых, инновационных технологий.

Методы. В статье рассматриваются основы метода полной дискретизации и его практическое применение. Этот метод является специальной модификацией метода конечных элементов для решения задач ползучести. Практическое применение метода иллюстрируется моделированием и прикладными задачами.

Результаты. В работе представлен совместный расчет системы «конструкция – фундамент – грунт» на примере резервуара модульной станции биологической очистки сточных вод, проектируемой для полей фильтрации в поселке Тасбогет Акмолинской области Республики Казахстан. Во всей расчетной области получена полная картина эволюции векторов перемещений, деформаций и напряжений во времени с учетом технологии возведения, проведено сравнение результатов расчета с учетом и без учета технологии возведения конструкций.

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