Numerical study of non-linear deformation processes of porous concrete

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Abstract. In the work, on the basis of the determining relations between the increments of the true stresses and strains, in the framework of the finite-element discretization of the computational domain, the method of solving geometrically and physically nonlinear problems of the mechanics of a deformable solid body is implemented. A number of model problems of deforming elements of three-dimensional elastoplastic structures from solid and porous materials have been solved. It may be noted that there is a good agreement between the numerical results obtained by the proposed method and known solutions; some regularities of the deformation of structural elements made of porous materials were found.

1. Introduction
Recent, large-scale simulation computer models have been widely used in the design and optimization of complex technical structures. Such models are well known and are used on a regular basis in the aviation and helicopter industries [1-7], the automotive industry, the transport industry, construction, and biology. In recent years, new materials have been actively used, including porous ones, models for which are used in computational geo- and biomechanics [8-13].

One of these areas forms the approaches based on the integrated application in the construction of mechanical and mathematical models of experimental and numerical methods, as well as on the use of scanning equipment to determine the microstructure of the material at all stages of its deformation. To solve a wide range of practical problems of deforming fine-grained porous media taking into account their microstructural changes, numerical calculation methods based on finite element discretization of a continuous medium are most often used.

Despite the fact that numerical solutions of the problems of the mechanics of a deformable solid body are widely used and implemented in many modern applied software packages [14-18], the specificity of the effect of changing the microstructure on the process of macroscopic deformation leads to considerable difficulties in their practical application.

Currently, a significant part of computational methods is based on regular discretization of the computational domain, and for the calculation, mainly finite element, boundary element and finite difference methods are used [19-26].

There are numerical approaches to solving the equations of the mechanics of a deformable solid, practically implemented, for example, in computer programs such as ANSYS or ABAQUS, but the great difficulty in practical implementation arises because of the peculiarities of the deformation of their microstructure on the macroscopic behavior of fine-grained porous materials.
2. Statement of the problem and numerical results

The construction of the computational algorithm is based on the discretization of the computational domain in the framework of the finite element method. On the basis of the previously implemented finite element method [27–33], which allows, based on the defining relations between the increments of true stresses and strains, simulate the deformation processes of the structural elements of fine-grained porous concretes under single and multiple loading. In the framework of the problem of elastoplastic deformation of elements of three-dimensional structures, models of isotropic and kinematic hardening of elastoplastic materials were used.

The constitutive equations connecting the components of the increments of true stresses $\sigma_{ij}$ and true deformations $\varepsilon_{ij}^{\text{true}}$ are chosen in the form

$$\Delta \sigma_{ij} = \frac{E}{1-2\mu} \delta_{ij} \Delta \varepsilon_{ij}^{\text{true}} + 2G \Delta \varepsilon_{ij}^{\text{true}} - \alpha \left( \sigma_{ij} \right)^2 \left( H_{ij}^{(1)} / 3G + 1 \right) \sigma_{ij}'.$$

To solve problems of contact interaction of structures, a special contact element with specific properties is used [27–30], the resolving equation is written based on the principle of virtual displacements in a variational form:

$$\sum_{m} \left[ \int_{\Omega_m} \{ \sigma_i \}^T \{ \delta \varepsilon_i \} d\Omega + \int_{\Omega_m} \sum_{k} \{ \sigma_{ij} \} ^T \{ \delta \varepsilon_{ij} \} d\Omega = \int_{\Omega_m} \sum_{k} \rho \{ g \} ^T \{ \delta V \} d\Omega + \int_{S_c} \{ P \} ^T \{ \delta V \} dS \right].$$

Based on the proposed algorithm, the problems of stretching and compressing the sample in the form of a parallelepiped made of solid and porous concrete were solved. For porous concrete, the case was considered when the pores have a cubic shape and are evenly distributed throughout the volume, the porosity was assumed to be 1/27.

To illustrate the results obtained, Figures 1 and 2 show the deformation diagrams with different hardening parameters, which were chosen in the Odquist form, for elastoplastic models with isotropic and kinematic hardening, respectively.

Figure 3 shows the dependence of the normal stresses on the axial displacements of the end of the computational domain for elastic and elastoplastic material models with isotropic linear hardening for solid and porous concrete.

![Figure 1. Strain diagram of porous sample with isotropic hardening.](image-url)
3. Analysis of the results and conclusions
For the problem of stretching a sample made of porous concrete, we can note the satisfactory coincidence of the Young's modulus, obtained on the basis of the proposed numerical technique and determined theoretically. The difference in their definition is explained by a rare finite element mesh. The yield strength of a porous sample is naturally lower than the yield strength of a continuous sample. It can be noted that the onset of plastic deformation in the sample is likely to be determined by the minimum cross-sectional area of the sample. Therefore, its pore size can also affect its size. The modulus of tangential hardening of the porous material is also reduced compared with the corresponding module for a solid sample. But it can be noted that during unloading and further loading of the porous sample, this module remains unchanged. As the voltage level increases, the tangential hardening modulus remains unchanged, but unloading and subsequent loading follow a linear law, the modulus of which is well below the elastic modulus of the sample material.

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References
[1] Kasumov E V 2013 TsAGI Science Journal 44 (2) 74-83
[2] Kasumov E V 2013 TsAGI Science Journal 44 (4) 64-71
[3] Kasumov E V and Gajnutdinov V G 2013 *Vestnik KGTU im. A.N.Tupoleva* 4 7-12
[4] Kasumov E V 2013 *Izv. VUZ. Aviatsionnaya Tekhnika* 3 11-14
[5] Kasumov E V 2014 *Izv. VUZ. Aviatsionnaya Tekhnika* 1 24-29
[6] Kasumov E V 2015 *TsAGI Science Journal* 46 (2) 63-75
[7] Kasumov E V, Basinov M E, Saltykov S V and Shuvalov V A 2015 *TsAGI Science Journal* 46 (5) 57-68
[8] Sachenkov O A, Gerasimov O V, Koroleva Y V, Mukhin D A, Yaikova V V, Akhtyamov I F, Shakirova F V, Korobeynikova D A and Chzhi K K 2018 *Russian Journal of Biomechanics* 22(3) 291-303
[9] Kharin N, Vorob'yev O, Bol'shakov P and Sachenkov O 2019 *Journal of Physics: Conference Series* 1158 (3) 032012
[10] Gerasimov O, Kharin N, Vorob'yev O, Semenova E and Sachenkov O 2019 *Journal of Physics: Conference Series* 1158 (2) 022046
[11] Gerasimov O, Koroleva E and Sachenkov O 2017 *IOP Conference Series: Materials Science and Engineering* 208 (1) 012013
[12] Kharin N V, Vorobyev O V, Berezhnoi D V and Sachenkov O A 2018 *PNRPU Mechanics Bulletin* 3 95-102
[13] Sachenkov O A, Hasanov R F, Andreev P S and Konoplev Y G 2016 *Russian Journal of Biomechanics* 20 (3) 220-232
[14] Badriev I B, Banderov V V and Zadzvornoy O A 2013 *Applied Mechanics and Materials* 392 188-190
[15] Badriev I B, Banderov V V and Makarov M V 2017 *IOP Conference Series: Materials Science and Engineering* 208 (1) 012002
[16] Badriev I B, Makarov M V and Paimushin V N 2017 *PNRPU Mechanics Bulletin* (1) 39-51
[17] Badriev I B, Banderov V V, Lavrentyeva E E and Pankratova O V 2016 *IOP Conference Series: Materials Science and Engineering* 158 (1) 012012
[18] Badriev I B 2013 *Applied Mechanics and Materials* 392 183-187
[19] Sultanov L U 2018 *Lobachevskii Journal of Mathematics* 39 (9) 1478-1483
[20] Golovanov A I and Sultanov L U 2005 *Prikladnaya Mekhanika* 41(6) 36-43
[21] Davydov R L, Sultanov L U and Kharzhavina V S 2015 *Global Journal of Pure and Applied Mathematics* 11 (6) 599-5108
[22] Abdrakhmanova A I, Sultanov L U and Fakhruddinov L R 2015 *Global Journal of Pure and Applied Mathematics* 11 (6) 5153-5162
[23] Golovanov A I and Sultanov L U 2005 *Prikladnaya Mekhanika* 41 (6) 36-43
[24] Panin V E 1990 *Strukturnyye urovni plasticheskoy deformatsii i razrusheniya* (Novosibirsk: Nauka) 255
[25] Panin V E, Likhachev V A and Grinyayev YU V 1985 *Strukturnyye urovni deformatsii tverdykh tel* (Novosibirsk: Nauka) 229
[26] Sadovsky M A 1979 *DAN USSR* 247 (4) 829-831
[27] Berezhnoi D V, Balafendieva I S, Sachenkov A A and Sekaeva L R 2016 *IOP Conference Series: Materials Science and Engineering* 158 012018
[28] Shamim M R and Berezhnoi D V 2016 *IOP Conference Series: Materials Science and Engineering* 158 012083
[29] Berezhnoi D V, Balafendieva I S, Sachenkov A A and Sekaeva L R 2017 *IOP Conference Series: Materials Science and Engineering* 204 012005
[30] Berezhnoi D V, Shamim R and Balafendieva I S 2017 *MATEC Web of Conferences* 129 03023
[31] Berezhnoi D V and Shamim R 2017 *Procedia Engineering* 206 1056-1062
[32] Berezhnoi D V and Paymushin V N 2005 *Naukoyemkiye tehnologii* 6 (8-9) 59-64
[33] Berezhnoi D V, Kuznetsova I S and Sachenkov A A 2010 *Uchenye Zapiski Kazanskogo Universiteta. Seriya Fiziko-Matematicheskie Nauki* 152 (1) 116-125