TEMPERATURE AND MOISTURE REGIME OF UNDERGROUND STRUCTURES

B. A. Krasovitskii and E. Yu. Kulikova

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The problem of heat and mass transfer between the air flow in an underground structure and the surrounding rock mass is considered. A method is developed for calculation of the air humidity, temperature and moisture fields in the rock mass.

Introduction. Effective operation of underground structures (US) necessitates that definite microclimatic parameters be maintained in them.

Microclimate of US develops under the influence of inner and outer heat and mass sources on the atmosphere of the structure.

Effective choice of the means for monitoring the microclimate requires a method for forecasting the heat and mass transfer between the structure and surrounding rock mass. The mutual thermal effect of US and the surrounding mass and the development of fluid flows between US and voids in the mass are components of the transfer process. The processes are interrelated. The rate of change of ventilation air temperature and humidity in US depends on the temperature and moisture fields in the surrounding mass. The contact between the moist rocks and air flow in US induces moisture migration towards the structure surface, because of which the moisture content in US increases and the adjacent rocks become dry. According to [1], in airways subject to long-time ventilation the moisture flow density amounts to 2-10 g/($m^2 \cdot h$).

In this article the mathematical problem of heat and mass transfer between US and the rock mass is posed including the effects enumerated. An approximate method is suggested for its solution, the calculation results obtained with the method are presented, and the features of the solutions are analyzed.

Statement of the Problem and Main Design Formulas. A cylindrical airway in an infinite rock mass is considered. An air flow with temperature and moisture content preset in the starting section moves along the airway with a known velocity. Equations, which describe the heat and mass transfer process in the assumed conditions will be written in a dimensionless form. The calculations will remain within the scope of simplifying assumptions, usually adopted in this class of problems [2]. The heat and vapor transfer equations in the ventilation air flow:

$$C_2 \frac{\partial \theta_a}{\partial x} = \theta_w - \theta_a + C_3; \tag{1}$$

$$D_2 \frac{\partial \varphi}{\partial x} = P(\theta_w, \varphi) + D_3. \tag{2}$$

The boundary conditions:

$$\theta_a|_{x=0} = 1; \tag{3}$$

$$\varphi|_{x=0} = 1. \tag{4}$$

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It is assumed that water migration in the rock mass occurs in a liquid phase following Fick's law; heat is transferred by conduction. Under these conditions the dimensionless heat and mass transfer equations in the mass will be written as

$$\frac{\partial\theta}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\theta}{\partial r}\right); \tag{5}$$

$$\frac{\partial U}{\partial t}=\frac{1}{r}\frac{a_{m2}}{\varkappa}\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r}\right). \tag{6}$$

The initial conditions:

$$\theta|_{t=0}=0;\quad U|_{t=0}=0.$$

The boundary conditions:

$$\left.\frac{\partial\theta}{\partial r}\right|_{r=1}=\alpha_{\mathrm{s}}(\theta_w-\theta_{\mathrm{a}})+LP(\theta_w,\ \varphi); \tag{7}$$

$$\left.\frac{\partial U}{\partial r}\right|_{r=1}=\frac{P(\theta_w,\ \varphi)}{M}. \tag{8}$$

We introduce the following dimensionless variables and parameters:

$$r=\frac{\bar r}{R_0};\quad x=\frac{\bar x}{L_{\mathrm{s}}};\quad t=\frac{(\tau-\tau_0)\varkappa_{\mathrm{T}}}{R_0^2};\quad \theta=\frac{T-T_0}{T_{\mathrm{a}0}-T_0};$$

$$\theta_w\equiv\theta|_{r=1};\quad \theta_w=\frac{T_{\mathrm{a}}-T_0}{T_{\mathrm{a}0}-T_0};\quad U=\frac{u_2-u_{20}}{u_{20}};$$

$$\varphi=\frac{\bar\chi}{\chi_0};\quad P=\frac{p_{\mathrm{ss}}-p_{\mathrm{pa}}}{p_{\mathrm{as}0}-p_{\mathrm{pa}0}};\quad \alpha_{\mathrm{c}}=\frac{R_0}{\lambda_{\mathrm{T}}\left(\dfrac{1}{\bar\alpha_{\mathrm{c}}}+\dfrac{R_i}{\lambda_{\mathrm{in}}}\ln\dfrac{R_0}{R_i}\right)};$$

$$L=\frac{r_{12}(p_{\mathrm{as}0}-p_{\mathrm{pa}0})}{\left(\dfrac{1}{R_i\alpha_{\mathrm{ms}}}+\dfrac{g\rho_1}{\lambda_{\mathrm{mc}}^{\mathrm{in}}}\ln\dfrac{R_0}{R_i}\right)}\,\frac{1}{\lambda_{\mathrm{T}}(T_{\mathrm{a}0}-T_0)}\left(\frac{R_0}{R_i}\right);$$

$$M=\frac{\gamma a_{m2}u_{20}}{(p_{\mathrm{as}0}-p_{\mathrm{pa}0})}\left(\frac{1}{R_i\alpha_{\mathrm{ms}}}+\frac{g\rho_1}{\lambda_{\mathrm{mc}}^{\mathrm{in}}}\ln\frac{R_0}{R_i}\right);$$

$$C_2=\frac{R_iv_xc_{\mathrm{B}}\rho_{\mathrm{B}}}{2L_{\mathrm{s}}}\left(\frac{1}{\bar\alpha_{\mathrm{s}}}+\frac{R_i}{\lambda_{\mathrm{in}}}\frac{R_0}{R_i}\right);$$

$$C_3=\frac{(q_{\mathrm{in}}^{l}-r_{12}I_1)}{2\pi R_i(T_{\mathrm{a}0}-T_0)}\left(\frac{1}{\bar\alpha_{\mathrm{s}}}+\frac{R_i}{\lambda_{\mathrm{in}}}\ln\frac{R_0}{R_i}\right);$$

$$D_2=\frac{R_iv_x\chi_0\rho_{\mathrm{a}}\left(\dfrac{1}{\alpha_{\mathrm{ms}}}+\dfrac{R_ig\rho_1}{\lambda_{\mathrm{mc}}^{\mathrm{in}}}\ln\dfrac{R_0}{R_i}\right)}{L_{\mathrm{B}}(p_{\mathrm{as}0}-p_{\mathrm{pa}0})};$$

$$D_3=\frac{I_{\mathrm{in}}}{2\pi(p_{\mathrm{as}0}-p_{\mathrm{pa}0})}\left(\frac{1}{R_i\alpha_{\mathrm{ms}}}+\frac{g\rho_1}{\lambda_{\mathrm{mc}}^{\mathrm{in}}}\ln\frac{R_0}{R_i}\right).$$

First, we consider solution of the problem (5)-(8). With the assumption of a small time change of the air temperature in the section considered, the problem will be solved with the integral method [3]. We obtained the dimensionless temperature profile in the mass within the heat disturbance region $1 \le r \le R_h$:

$$\theta=\frac{\theta_w\left(R_h-r+R_h\ln\dfrac{r}{R_h}\right)}{R_h-1-R_h\ln R_h}. \tag{9}$$

Here $\theta_w \equiv \theta|_{r=1}$; R_h is the dimensionless radius of the thermal effect, defined as in [3].

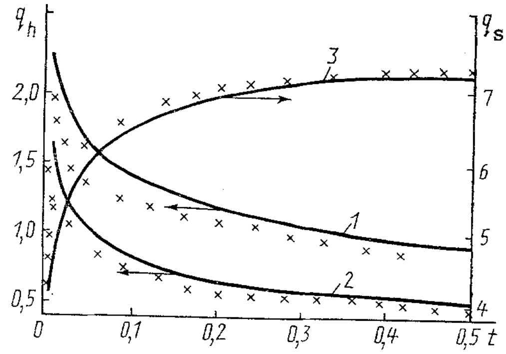

Fig. 1. Comparison of the approximate analytical (curves) and numerical (dots) solution of the problem (5)-(8): 1, 2) $q_{in}(t)$ (moisture migration neglected and included); 3) $q_{in}(t)$; $q_h \equiv \partial\theta/\partial r|_{r=1}$; $q_{in} \equiv \partial U/\partial r|_{r=1}$.

Substituting Eq. (9) into the boundary condition (7), we arrive at the transcendental equation for θ_w:

$$\frac{\theta_w (R_h - 1)}{R_h - 1 - R_h \ln R_h} = \alpha_s(\theta_w - \theta_a) + LP(\theta_w,\ \varphi). \tag{10}$$

Now, proceed to the problem (6), (8) of moisture transfer in the rock. Using the same method as was employed in the temperature problem, we express the dimensionless moisture content as

$$U = \frac{U_w\left(R_d - r + R_d \ln \dfrac{r}{R_d}\right)}{R_d - 1 - R_d \ln R_d}. \tag{11}$$

where R_d is the dimensionless radius of the diffusion effect defined by the relation

$$R_d(t) \equiv R_h\left(\frac{ta_{m2}}{\varkappa}\right). \tag{12}$$

The substitution of Eq. (11) into the boundary condition (8) gives the equation for U_w

$$\frac{U_w (R_d - 1)}{R_d - 1 - R_d \ln R_d} = \frac{P(\theta_w,\ \varphi)}{M}. \tag{13}$$

In order to estimate the accuracy of the method, the problem (5)-(8) was solved numerically with the finite difference method [4]. The values of the dimensionless temperature and moisture gradients at the airway wall at different times were compared. The comparison results are given in Fig. 1. The deviations are within 7%.

Thus, the problem of heat and moisture transfer in the air flow posed in this way is solved separately from the problem of moisture migration in the rock mass. It is assumed here that the rate of moisture flow from the mass to the airway surface provides an air flow from the surface to the air defined by the difference of partial pressures of saturated steam in the near-surface voids and steam in the air.

The problem of determining the temperature and moisture content in a cylindrical airway with a circular cross section reduces to integration of a set of two ordinary differential equations of the first order (1) and (2) with the boundary conditions (3) and (4) and with Eq. (10).

When the rate of moisture flow from the mass to the airway surface becomes smaller than that of moisture flow from the surface into the air, the near-surface rock layer starts to dry. In that layer the moisture content drops below the maximal hygroscopic moisture contents u_{2h}, and moisture is transferred only as vapor. In the other region it may be assumed that the whole moisture transport occurs in the liquid phase [5]. Hence it follows that moisture evaporation takes place in a narrow region near the drying boundary r = s where

$$u_2|_{r=s+0} = u_{2g};\quad u_2|_{r=s-0} = p_{2p}. \tag{14}$$

Using the notion of a mass conductivity λ_{mc}, we write the boundary conditions at the evaporation surface and at the airway surface as follows:

$$U|_{g=s+0} = U_g; \tag{15}$$

$$\frac{P}{R_s + \ln s} = N_2 \frac{\partial U}{\partial r}\bigg|_{r=s+0} + L_2 \frac{ds}{dt}; \tag{16}$$

$$-l_s \frac{\partial \theta_s}{\partial r}\bigg|_{r=s-0} + \frac{\partial \theta_T}{\partial r}\bigg|_{r=s+0} = \frac{L_s P}{(R_s + \ln s)}; \tag{17}$$

$$\frac{\partial \theta_s}{\partial r}\bigg|_{r=1} = \alpha_{ds}(\theta_c - \theta_a)|_{r=1}; \tag{18}$$

$$\theta_s|_{r=s-0} = \theta_T|_{r=s+0} = \theta_s. \tag{19}$$

Here

$$L_s = \frac{r_{12}\lambda_{ms}(p_{as0} - p_{pa0})}{g\rho_1\lambda_T(T_{a0} - T_0)}\left(\frac{R_0}{R_i}\right);$$

$$\alpha_{ds} = \frac{R_0}{\lambda_s\left(\dfrac{1}{\alpha_c} + \dfrac{R_i}{\lambda_{in}}\ln\dfrac{R_0}{R_i}\right)};$$

$$N_2 = \frac{\rho_1\gamma g a_{m2} u_{20}}{\lambda_{ms}(p_{as0} - p_{pa0})}\left(\frac{R_i}{R_0}\right); \quad l_c = \frac{\lambda_c}{\lambda_T};$$

$$L_2 = \frac{(u_{2r} - u_{2p})\varkappa_T\gamma g\rho_1}{\lambda_{ms}(p_{as0} - p_{pa0})}\left(\frac{R_i}{R_0}\right); \quad s = \frac{\bar{s}}{R_0};$$

$$R_c = \lambda_{ms}\left[\frac{1}{R_i g\rho_1\alpha_{ms}} + \frac{1}{\lambda_{ms}^{in}}\ln\frac{R_0}{R_i}\right].$$

The heat conduction equation in the dried and moist regions:

$$\frac{\partial \theta_a}{\partial t} = \frac{a_c}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \theta_a}{\partial r}\right); \quad 1 \leqslant r \leqslant s, \tag{20}$$

$$\frac{\partial \theta_T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \theta_T}{\partial r}\right); \quad r \geqslant s. \tag{21}$$

The liquid moisture migration equation (6) holds in the region $r \geq s$.

Consider the approximate method for this problem solution. As before, introduce regions of thermal $s \leq r \leq R_h$ and migratory $R_d \geq r \geq s$ disturbance. First, we consider the problem for the temperature field. The solution will be sought in the dried region $1 \leq r \leq s$ as a quasisteady logarithmic profile:

$$\theta_a = \theta_s + \frac{\theta_s - \theta_a}{\left(\dfrac{1}{\alpha_{ds}} + \ln s\right)}\ln\frac{r}{s}. \tag{22}$$

Similarly to Eq. (9), the temperature profile in the moist rock region will be assumed in the form

$$\theta_T = \frac{\theta_s\left(R_h - r + R_h\ln\dfrac{r}{R_h}\right)}{R_h - s - R_h\ln\dfrac{R_h}{s}}. \tag{23}$$

The expressions satisfy the conditions at the boundary of the thermal disturbance region and conditions (16), (18), (19). Substituting them into condition (17), we arrive at the transcendental equation

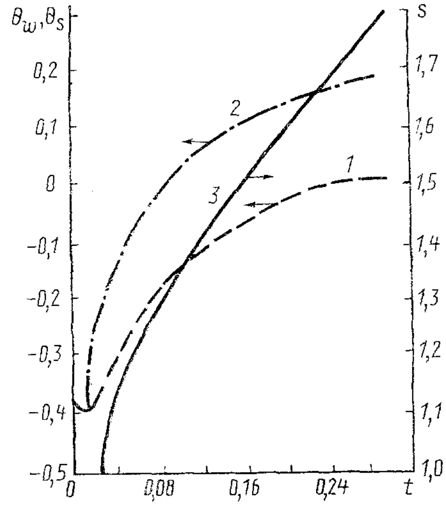

Fig. 2 Calculation results for the plane problem: 1) $\theta_w(t)$; 2) $\theta_s(t)$; 3) s(t).

$$-l_c \frac{(\theta_s - \theta_a)}{\left(\frac{1}{\alpha_{ds}} + \ln s\right) s} + \frac{\theta_s\left(\frac{R_h}{s} - 1\right)}{(R_h - s - R_h \ln R_h)} = \frac{L_s P(\theta_s, \varphi)}{R_c + \ln s}. \tag{24}$$

Thus, for determining the three unknown functions $\theta_s(t)$, s(t), and $R_h(t)$ we have Eq. (24) and the function $R_h = R_h(t)$ [3]. The missing relation will be sought from consideration of moisture transfer.

As in the case of Eq. (11), with the condition (15) and conditions at the boundary of migratory disturbance region the expression for dimensionless moisture content in the region $s \leq r \leq R_d$ will be sought in the form

$$U = \frac{U_h\left(R_d - r + R_d \ln \frac{r}{R_d}\right)}{R_d - s - R_d \ln \frac{r}{R_d}}. \tag{25}$$

The substitution of Eq. (25) into the condition (16) yields

$$\frac{P(\theta_s, \varphi)}{R_s + \ln s} = \frac{N_2 U_h\left(\frac{R_d}{s} - 1\right)}{R_d - s - R_d \ln R_d} + L_2 \frac{ds}{dt}. \tag{26}$$

The values of R_h and R_d will be determined for each time moment, then the unknown functions s(t) and $\theta_s(t)$ will be found from the set of Eqs. (24) and (26). With these functions, using Eqs. (22), (23), and (25), we will determine the temperature and moisture distribution for every time moment.

The algorithm may be employed when the air temperature and humidity in the section considered are known. When it is necessary to find the temperature and humidity of ventilation air, the heat and vapor transfer equation in the flow should be added to the set of Eqs. (15)-(21)

$$C_2 \frac{\partial \theta_a}{\partial x} = \theta_w - \theta_a + C_3; \tag{27}$$

$$D_2 \frac{\partial \varphi}{\partial x} = \frac{P(\theta_s, \varphi)}{1 + \frac{1}{R_s} \ln s} + D_3. \tag{28}$$

The relations (3) and (4) serve as boundary conditions for the equations.

The set (27), (28) is integrated with a numerical method. In every plane section, starting with the section x = 0, we determine s, θ_s, and θ_w with the algorithms developed for the plane problem. With these values, from the set (27), (28) we estimate θ_a and φ in the subsequent section where the procedure is repeated.

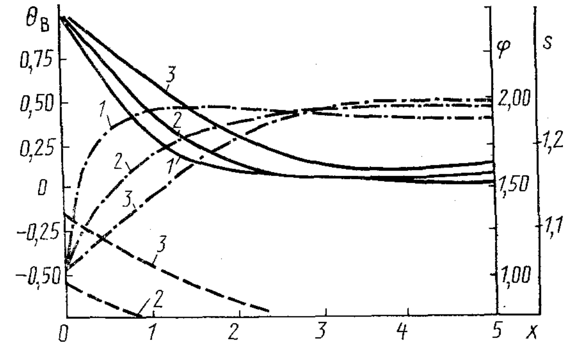

Fig. 3. Variation of the dimensionless temperature (solid curves), dimensionless moisture content of ventilation air (dotted–dashed lines) and the dried region configuration (dashed curves) for different times: 1) t = $4 \cdot 10^{-4}$; 2) 0.087; 3) 0.5.

In Fig. 2 the calculation results are presented for heat and mass transfer around the airway with known temperatures and moisture contents of ventilation air (the plane problem). The calculations were conducted with the following initial data: T_{a0} = 20°C; T_0 = 5°C; $\bar{\chi}$ = 0.002; λ_T = 1.16 W/(m·deg); λ_a = 1 W/(m·deg); R_0 = 4.75 m; R_i = 4.73 m; λ_{in} = 1.16 W/(m·deg); λ_{mc}^{in} = $0.32 \cdot 10^{-11}$ kg/(m^2·sec); λ_{mc} = $0.62 \cdot 10^{-11}$ kg/(m^2·sec); u_{2h} = 0.1; u_{20} = 0.2; a_{m2} = $0.4 \cdot 10^{-8}$ m^2/sec; γ = 2000 kg/m^3; κ_T = $0.472 \cdot 10^{-6}$ m^2/sec; ρ_1 = $0.484 \cdot 10^{-3}$ kg/m^3.

It is noteworthy that in this example at the beginning of the process $\theta_w(0) < 0$, subsequently θ_w decreases to the initial formation of the dried region. The decrease can be explained by the fact that in this case the heat flow is directed towards the evaporation front and as it reduces and the mass is cooled, the temperature of the evaporation surface drops.

Figure 3 shows the calculated temperatures and moisture contents of ventilation air and the dried region configuration along the structure length at different times (the conjugate problem).

Conclusion. The problem of heat and mass transfer between the ventilation air in an underground structure and the surrounding rock mass is mathematically formulated. Approximate analytical and numerical methods, and a computer program based on the methods are developed, variations of the parameters of ventilation air, temperature and moisture fields in the rock mass, and the dried region configuration are calculated. Comparison of the analytical and numerical methods has shown good agreement.

The method can be used for choosing the US design parameters, ensuring a required air temperature and humidity and for developing software for computer-aided control of conditioning systems.

NOTATION

τ, time, sec; τ_0, starting moment of operation, sec; $\bar{r}$, radial coordinate, m; R_0, outer radius of heat and water insulation of the structure, m; R_i, flow section radius, m; $\lambda_t(\lambda_d)$, thermal conductivity of moist (dried) mass, W/(m deg); $\kappa_t(\kappa_d)$, thermal diffusivity of moist (dried) mass, m^2/sec; λ_i thermal conductivity of the insulation, W/(m^2·deg); $\bar{\alpha}_i$, coefficient of heat transfer from the air to inner surface of the structure, W/(m^2·deg); T_a, air temperature, °C; T_0, natural temperature of the rock mass at the depth of foundation, °C; u_2, natural moisture content of the rock mass; u_{2h}, maximum hygroscopic moisture content; u_{2e}, equilibrium moisture content; $\bar{\chi}$, section-averaged air humidity, kg vapor/kg dry air; κ_0, the same in the starting section; p_{as}, saturated steam pressure at the evaporation surface temperature, Pa; p_{pa}, partial steam pressure in the air; p_{as0} saturated steam pressure at T_{a0}; p_{pa0}, partial steam pressure in the starting section, Pa; r_{12}, specific vaporization heat, J/kg; α_{ms}, coefficient of mass transfer from the air to inner surface, kg/(m^2·sec·Pa); λ_{mc}, mass conductivity of the rock mass, kg/(m^2·sec); λ_{mc}^{in}, the same for water insulation; g, gravitational acceleration, m/sec^2; ρ_1, steam density, kg/m^3; γ, volumetric density of the rock mass skeleton, kg/m^2; v_x, air flow velocity, m/sec; c_a, specific heat of the air, J/(kg·deg); ρ_a, air density, kg/m^3; q_{hs}^1, heat rate of inner sources in the structure per meter run, W/m; I_1, vaporization rate in the air volume per meter run, kg/(m·sec); I_{As}, intensity of inner steam sources, kg/(m·sec); $\bar{s}$, dried region radius; T_w, temperature of the outer water isolation surface; T_s, temperature at the dried region boundary; a_{m2}, potential conductivity of the rock mass, m^2/sec; $\bar{x}$, longitudinal coordinate, m; L_s, structure length, m; T, rock mass temperature, °C.

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THE EFFECTIVE PERMEABILITY TENSOR OF HEAVILY INHOMOGENEOUS GROUNDS

S. E. Kholodovskii

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A method is developed for the construction of the effective permeability tensor in an anisotropic model of nondeformable grounds with a complicated structure, consisting of systems of mutually parallel layers, joints, and slightly permeable screens (interlayers), enclosed in one another (each layer of one system consists of arbitrary oriented layers, joints and screens of another). A new filtration model of joints and screens is suggested.

Filtration processes are usually associated with expressed inhomogeneity of natural grounds because of their stratified structure, jointing, presence of slightly pervious screens, etc. [1, 2]. Tectonic joints and screens often appear at the interface of heterogeneous layers and form substantially regular systems [2, 3] such as free and sealed slits, veins, and interlayers.

Accurately posed filtration problems in stratified grounds (conjugation problems) were solved in a general form for two, three, and four homogeneous zones (layers), separated by straight lines and circumferences (see the review in [4]). Numerous approximate methods have been developed for the conjugation problems with an arbitrary number of layers ([5-7] et al.). For systems of layers enclosed in one another the conjugation problem is essentially complicated, and in its solution the properties of grounds are globally averaged, i.e. their effective filtration parameters are determined. In [8-10] tensors of effective permeability were found for one system and two systems of mutually orthogonal periodical of layers. For jointly (cracked) porous media a model was suggested in [11] as two mutually penetrating continua with an average scalar permeability of blocks and joints. The effective permeability tensors were constructed for nondeformable [2, 3] and deformable [12, 13] jointly grounds. The authors quoted considered relatively simple structures of jointly grounds when the blocks are either impermeable or permeable and homogeneous. Moreover, the liquid flow in a joint is based on the model of viscous liquid motion through a channel with impermeable walls, and according to the model, hydraulic permeability of the joint is proportional to the cube of its opening (Boussinesq's formula) [2, 3, 6, 9, 12], that is permeability of fine joints is negligibly small. This model, based on the lubrication theory [14], is sufficiently idealized in the filtration theory where the wall surfaces of the joints are usually permeable and can be in contact at several points, the joints being partially or fully filled with debris materials [2]. As regards filtration, a joint is a layer, whose thickness is much smaller and permeability much larger than the characteristic parameters of the ground.

The article describes a method for constructing the effective permeability tensors for nondeformable grounds, which consist of arbitrary oriented anisotropic inhomogeneous systems of layers, joints and screens enclosed into one another with an arbitrary depth of enclosure. Moreover, a filtration model of joints and screens is suggested in the form of degenerating layers of

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