Evaluation of Pore Pressure of Core for Vedi Hydropower Dam

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Abstract. Quantitative assessment have been done for the hydrodynamic force generated in the core of Vedi hydroelectric dam during the construction and after its completion, as the lack of studies in the direction of it can reduce the stability of both the core and the dam slopes, which finely can arise the security issues for structure. An appropriate calculation scheme is considered, where as an initial data the physical and mechanical parameters were taken for the dam core and the actual construction dates. The assessment of porous pressure was performed by Volfram Mathematics 7 computer program for two calculation cases: a) the construction of layers of the dam core at a constant speed, b) the conditions of gradual filling of the reservoir, with the change of the pressure condition on the core. The obtained results can be used to determine the stability of the dam core, as well as the deformation of the core and side prisms.

Indroduction

The purpose of building a Vedi earth-rock dam is to increase the level of agricultural production in the Ararat Valley. 1675 hectares of Vedi and 1545 hectares of Ararat lands will be irrigated by gravity through the reservoir. The main dam of the Vedi hydroelectric dam is a first-class earth-rock dam with 85m of height and central core [1].

During the construction of the Vedi dam, porous pressure may develop in the clay core, which may reduce the stability of both the core and the slopes, causing safety problems. The porous pressure in the clay core of the dam is required to check the slip stability of the core, both during construction and after the filling of dam reservoir.

Consolidation porosity pressure is the hydrodynamic pressure that occurs during condensation in waterlogged soils under the influence of external loads or its own weight. In earth-rock dams, it occurs in the compacted water-saturated soils of the dam core, during the construction of the layers and further consolidation. The pore pressure is an additional sliding force for the core and slops, as the load increases "rapidly" or "instantaneously" when the next layer of soil is placed on the previous one, but the ground resistance does not increase as it slides. In saturated soils, the "instantaneously" applied load is completely transferred to the water trapped in the soil pores, the soil particles are not compressed. During this the ground density does not increase and an instantaneous increase in sliding force is obtained without increasing the slip resistance. Later, water is pumped out from the pores, the load is transferred to the ground frame, as a result it compacts, the sliding resistance increases. The movement of porous water is variable over time and it is a non-stationary movement. The intensity of the movement depends on the degree of groundwater saturation, the filtration coefficient, as well as the drainage conditions, the connection with the transfer layers (contact) of the core.

As the porous pressure has a negative effect on the stability of the slops, therefore, according to the norms [2,3] for the dams higher than 40m the static calculations of the slops is mandatory in all cases when the core soils are fine clay, waterlogged, have $\geq 0{,}85$ humidity and filtration coefficient less than $(5 \ldots 10)10^{-6}$ cm/s.

The differential equations for the consolidation of the filtration of fully saturated soils for a uniform problem were given by Tertsagi, further developed in the works of N.M. Gersevanov. The basic computational model of the ground environment was adopted by V.A. Florin [4] consisting of three phases: solid (ground structure), liquid (water in the pores) and gaseous (air in the pores - partial water) phases.

Filtration fastening the V.A. Florin model is well suited for construction of earth-rock dams made from local materials, that is why it is so popular. The main purpose of this calculation model is to study the consolidation of soil and to calculate the reduction of water content accompanying with compaction. The ground is considered where the content of gas (air, water vapor) is not more than 10-15% of the pore volume. The purpose of the ground reinforcement theory is to determine the distribution of the load acting on the ground between solid and liquid phases. The solution of this question is very important, because only the forces acting on the solid phase generates the ground friction forces, which determines the stability of soil structures.

The amount of porous pressure in the dam core depends on the following parameters: filtration coefficient, density, water saturation, elastic-plastic properties, geometric dimensions of the core, construction time, etc.

The first three of these factors have a decisive effect. For example, in the case of large filtration coefficients $(k > 10^{-3}...10^{-4})$ cm/s, a small pore pressure is generated during the construction of the core.

In case of small filtration coefficients $(k < 10^{-7}...10^{-8})$ cm/s and full water saturation the pore pressure reaches about 100% at the end of construction. At average values of filtration coefficients $(k = 10^{-5}...10^{-6})$ cm/s, the porous pressure develops partially. Since the filtration, porosity and condensation coefficients are in the form of a ratio in the consolidation formulas $k(1+\varepsilon)/a$, therefore, the effect of changes in their magnitude associated with height is small.

Calculation method

The porous pressure calculations are based on the theory of soil compaction filtration theory, as well as the solution of mixed problems of filtration consolidation and landslide theories.

V.A. Florin have made the three-phase ground invulnerability equation, by help of it obtained the consolidation equation for a three-phase soil environment, in the case of the flat deformation it has the following appearance [4,5,6,7,8]:

$$\frac{1}{1+\varepsilon}\frac{\partial \varepsilon}{\partial t} + \beta \frac{\partial P_B}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial H}{\partial z}\right), \tag{1}$$

where ε-is the porosity coefficient, β-is the gas volumetric compression coefficient, P_B-is the porosity pressure, k_x and k_z are the core filtration coefficients in the horizontal and vertical directions, H - is the pressure function, t - is the time.

For this equation A.A. Nichiporovich and T.I. Tsibulnik have obtained the solutions in closed view, assuming that the ground characteristics and medium stresses in the horizontal sections of the core are constant.

The smooth problem in terms of filtration can be brought to one-dimensional if we assume that the water leaves the core in a horizontal direction to the transfer zones, which is equivalent to a large filtration anisotropy in the ground $k_x >> k_z$. ε, a, k - the values according to the height of the core are taken as variable and within each layer they are constant, equal to their average values. The checks of this acceptance by various authors have shown that it does not cause significant error for thin-walled filtration elements (core, screen).

The pore pressure is determined during the construction of the core in the conditions of an empty reservoir and during the filling of the reservoir. The purpose of the calculation is to determine the pore pressure at any point in the dam core (Fig. 1a, b).

1. Under conditions of constant velocity the construction of the dam core (Fig. 1a, b), at any point in the core, at any time, the pore pressure due to the weight of the next layer of soil is determined according to A.A. Nichiporovich expression [9].

$$P_{B,g}\left(x,z=const,t\right)=\frac{4\alpha^{I}U}{\mu\pi}\sum_{i=1,3,5...}^{\infty}\frac{1}{i^{3}}\left[e^{-i^{2}\mu(t-t_{k})}-e^{-i^{2}\mu(t-t_{z})}\right]\sin\frac{i\pi(\ell_{z}-x)}{2\ell_{z}}, \quad (2)$$

where t – is the time of consolidation, t_k - is the the of construction of the dam, and t_z – is the time of construction of the dam core up to the z level, U -is the rate of increase of the load:

$$U=\frac{\gamma_1 H_1}{t}, \qquad t_Z=\frac{\gamma_1 z}{U}=\frac{z}{H_1}t_K, \quad (3)$$

$$\mu=\frac{\pi^2}{4\ell_z^2}\cdot C\lambda, \quad (4)$$

where γ_1- is the specific gravity of the wet ground, H_1- is the height of the core, a- is the coefficient of soil compaction, ℓ_z- is half of the width of the core at z level calculated from the base, γ_0- is the specific gravity of the water, C- is the consolidation coefficient, k- is the ground filtration coefficient, and the λ- coefficient is determined by the following expression:

$$\lambda=\frac{(P_0+\alpha^I P_n)^2}{(P_0+\alpha^I P_n)^2+\frac{1+\varepsilon}{a}P_0V_0}, \quad (5)$$

where- P_0- is the atmospheric pressure, V_0- is the initial volume of air in the ground per unit volume, α^I - is the porous pressure coefficient, $\alpha^I=P/P_n$, P_n is the amount of pressure caused by the placement of one layer to another which is determined by the following expression $P_n=\gamma_1(H_1-z)$.

2. In the case of gradual fill of the reservoir with change of pressure conditions, for determination the amount of porous pressure at any $t>t_s$ moment A.A. Nichiporovich and T.I. Tsibulnik [9,10] have obtained a general solution for porous pressure, it has the following view:

$$P_{B,S}(x,z=const,t)=V\gamma_0\left\{\frac{\ell_z-x}{2\ell_z}\left(t_s-t_{sz}\right)+\frac{2}{\pi\mu}\sum_{i=1,2,3,...}^{\infty}\frac{\alpha^I(i)}{i^3}\sin\frac{i\pi}{2\ell_z}(\ell_z-x)\left[e^{-i^2\mu(t-t_s)}-e^{i^2\mu(t-t_{sz})}\right]\right\}, \quad (6)$$

where V - is the velocity of the reservoir,

$$V=\frac{H}{t_s-t_H}, \quad (7)$$

where $\alpha^I(i)=\alpha^I+(-1)^i(1-\alpha^I)$.

In the case of a pair of values, $\alpha^I(i) = 2\alpha^I - 1$, in the case of odd values of i, H -is the water depth on structure, t_H, t_S -is the time for beginning and the end of the reservoir filling.

Calculation of pore pressure in case of Vedi dam

For the observed cases, it is necessary for determine the pore pressure values of the Vedi dam core with the expressions (2) and (6):

a) the geometric shape of the core and the size of the dam (Fig. 1a, b),

b) Physical-mechanical parameters of the core soils; Ground filtration, compaction, medium porosity (compression curve), water saturation coefficients, specific gravities of saturated soil and in non-saturated conditions, specific gravity of soil in contact with the core,

c) The construction schedule T_k core including the planned interruptions (construction and weather) and the actual construction period $T_F = T_k - T_0$, where T_0 - is the sum of the breaks.

The core of the dam is divided into 6 layers (Fig. 1b) with a height of 14.0 m. The construction of layers and filling duration of the reservoir are given in Table 1.

Table 1. Construction of dam core according to layers and reservoir filling duration

	Layers heights z, meters						
	0	14	28	42	56	70	84
Duration of layers installation, day, t_z	0	115	230	345	460	517	692
Reservoir filling duration, day, $t_{S,z}$	700	760	832	912	1000	1110	1250

Initial soil data for construction of core of Vedi dam[11].

H_1=84,0 m, k=0,0001 m/day, $t_K = 692$ day, $\varepsilon = 0{,}7$ (From the compression curve), $W = 26$ %, $\beta = 0{,}0245$, $a = 0{,}48*10^{-6}$ m²/kg, $P_0 = 10000$ kg/m², α^I =0,48, $\gamma_1 =$ 1840 kg/m³, $\gamma_0 = 1000$ kg/m³, $n = 41$ %, $2\ell_z = 36{,}6$ m. The coefficient of the slop of the dam core $m = 0{,}2$, t_S and $t_{S,z}$. The values of the quantities are given in Table 1.

a) b)

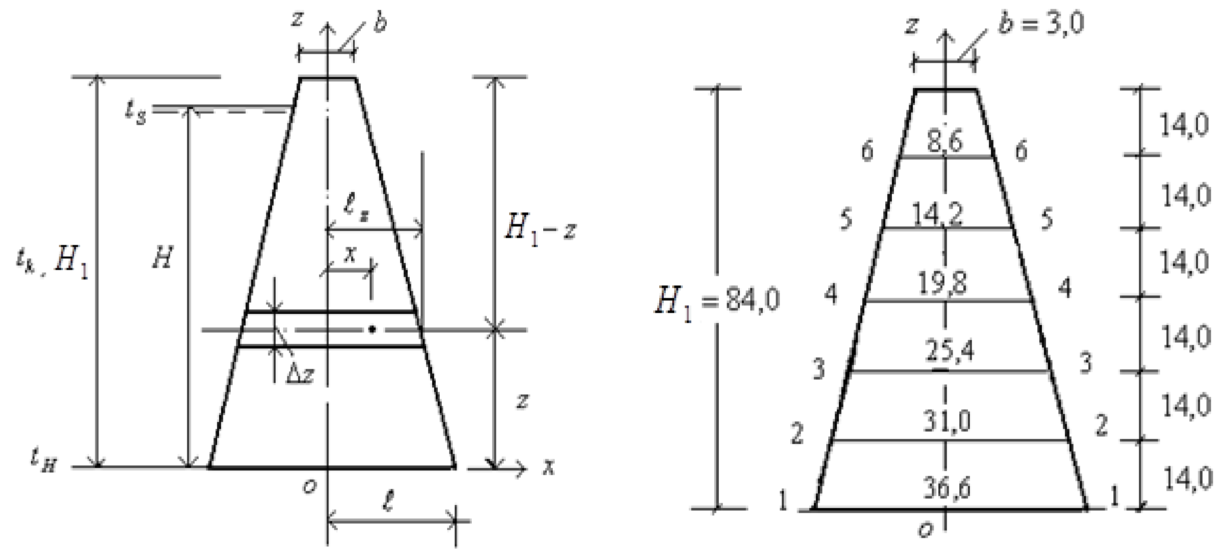

Fig. 1. Computational scheme for the determination of porous pressure in the core

a - The calculation scheme of pore pressure in any point of core Δz - the depth of layers, Δz =14m,

b - The construction scheme of core layers

The following parameters were determined for the calculation of the pore pressure.

1. The magnitude of the consolidation coefficient

$$C = \frac{k(1+\varepsilon)}{a\gamma_0} = \frac{0{,}0001\ \ (1+0{,}7)}{0{,}48\cdot 10^{-6}\cdot 1000} = 0{,}354 \text{ sm}^2\text{/s}.$$

2. The initial volume of air

$$V_0 = n(1-G) + \beta n G,$$

where $G = \frac{W\gamma_1(100-n)}{n\gamma_0} = \frac{0{,}26\cdot 1840\,(100-41)}{41\cdot 1000} = 0{,}688$, and $V_0 = 0{,}135$.

3. The load growth rate is

$$U = \frac{\gamma_1 H_1}{t_K} = \frac{1840\cdot 84}{692} = 223{,}4 \text{ kg/m}^2\text{s}.$$

4. μ and λ coefficients

$$\mu = \frac{\pi^2}{4\ell_z^2}\cdot\frac{k(1+e)}{a\gamma_0}\cdot\lambda = 0{,}873\frac{\lambda}{\ell_z^2}, \text{ where } \lambda = \frac{(P_0+\alpha^I P_n)^2}{(P_0+\alpha^I P_n)^2 + \frac{1+e}{a}P_0V_0}, \ P_n = \gamma_1(H - z).$$

The parameters of the porous pressure are determined by the above formulas (2-7) using these parameters. The results of the calculation are summarized in Tables 2-7.

Table 2. The values of the pore pressure parameters

Sections	z, m	ℓ_z, m	μ, 1/day	λ	P_n, kPa
1 – 1	0	18,3	0,00130	0,504	1545,6
2 - 2	14,0	15,5	0,00165	0,425	1288,0
3 - 3	28,0	12,7	0,00182	0,336	1030,4
4 - 4	42,0	9,9	0,00215	0,241	772,8
5 – 5	56,0	7,1	0,00255	0,147	515,2
6 - 6	70,0	4,3	0,00316	0,067	257,6

Table 3. The values of the porous pressure in the core construction conditions when $t = t_k = 692$ day

Sections	z, m	ℓ_z, m	t_z, day	$P_{B,g}$, kPa		
				$x = 0$	$x = 0{,}5\ell_z$	$x = \ell_z$
1 – 1	0	18,3	0	617,2	436,4	0
2 – 2	14,0	15,5	115	512,1	362,1	0
3 – 3	28,0	12,7	230	414,6	293.1	0
4 – 4	42,0	9,9	345	324,0	228,7	0
5 – 5	56,0	7,1	460	234,4	165,8	0
6 – 6	70,0	4,3	576	137,0	96,9	0

Table 4. The values of the porous pressure in the core construction conditions when $t = 1300$ day, $t_k = 692$ day

Sections	z, m	ℓ_z, m	t_z, day	$P_{B,g}$, kPa		
				$x = 0$	$x = 0{,}5\ell_z$	$x = \ell_z$
1 – 1	0	18,3	0	223,8	158,3	0
2 – 2	14,0	15,5	115	152,0	107,5	0
3 – 3	28,0	12,7	230	95,4	67,5	0
4 – 4	42,0	9,9	345	54,0	38,2	0
5 – 5	56,0	7,1	460	25,8	18,3	0
6 – 6	70,0	4,3	576	8,1	5,7	0

Table 5. The values of the porous pressure during the construction of the core and filling of the reservoir

z, m	ℓ_z, m	t_z, day	$P^I{}_{B,g}$, kPa			μ, 1/day	λ	P_n, kPa
			$x=0$	$x=0{,}5\ell_z$	$x=\ell_z$			
0	18,3	0	223,8	158,3	0	0,00113	0,433	1050,0
14,0	15,5	115	168,4	119,1	0	0,00113	0,362	875,0
28,0	12,7	230	119,8	84,7	0	0,00154	0,285	700,0
42,0	9,9	345	77,8	55,0	0	0,00184	0,206	525,0
56,0	7,1	460	42,1	29,8	0	0,0023	0,131	350,0
70,0	4,3	576	13,4	9,5	0	0,0031	0,066	175,0

Table 6. The values of the porous pressure during the filling of the reservoir, $t = 1300$ day

z, m	ℓ_z, m	$t_{s,z}$, day	$P_{B,S}$, kPa					μ, 1/day	λ	P_n, kPa
			$x=-\ell_z$	$x=-0{,}5\ell_z$	$x=0$	$x=0{,}5\ell_z$	$x=\ell_z$			
0	18,3	0	830,0	615,1	402,3	195,7	0	0,0016	0,598	1545,6
14,0	15,5	115	830,0	615,3	402,8	196,5	0	0,0019	0,520	1288,0
28,0	12,7	230	830,0	615,4	403,2	197,1	0	0,0023	0,426	1030,4
42,0	9,9	345	830,0	615,5	403,4	197,5	0	0,0028	0,317	772,8
56,0	7,1	460	830,0	615,5	403,4	197,6	0	0,0035	0,202	515,2
70,0	4,3	576	830,0	620,6	412,0	205,2	0	0,0045	0,095	257,6

Table 7. Total porous pressure from its own weight in the conditions of filling, the reservoir $t = 1300$ day

z, m	ℓ_z, m	t_z, day	$t_{S,z}$, day	$P^I_{B,g} + P_{B,S}$, kPa				
				$x=-\ell_z$	$x=-0{,}5\ell_z$	$x=0$	$x=0{,}5\ell_z$	$x=\ell_z$
0	18,3	0	700	830,0	615,1	626,1	354,0	0
14,0	15,5	115	760	830,0	615,3	571,2	315,6	0
28,0	12,7	230	832	830,0	615,4	523,0	281,6	0
42,0	9,9	345	912	830,0	615,5	481,2	252,5	0
56,0	7,1	460	1000	830,0	615,5	445,5	227,4	0
70,0	4,3	576	1110	830,0	620,6	425,4	214,7	0

Determining the pressure from its own weight, but in the case of filling the reservoir, the rate of the increase of the load was determined by assuming that the ground of the core is in a lightened condition, i.e.

$$U = U^I = \frac{\gamma_B^I H_1}{t}.$$

Applying the principle of summation, the total porous pressure from its own weight and filling of the reservoir (taking into account the lightening of the ground) was determined:

$$P = P^I_{B,g} + P_{B,S} ,$$

where $P^I_{B,g}$ - is counted in the case of γ_B^I.

Fig. 2a shows the porosity of the porous pressure in the core of the dam from its own weight of the core, without raising the water level in the upper stream and Fig. 2b takes into account also the increase of water level.

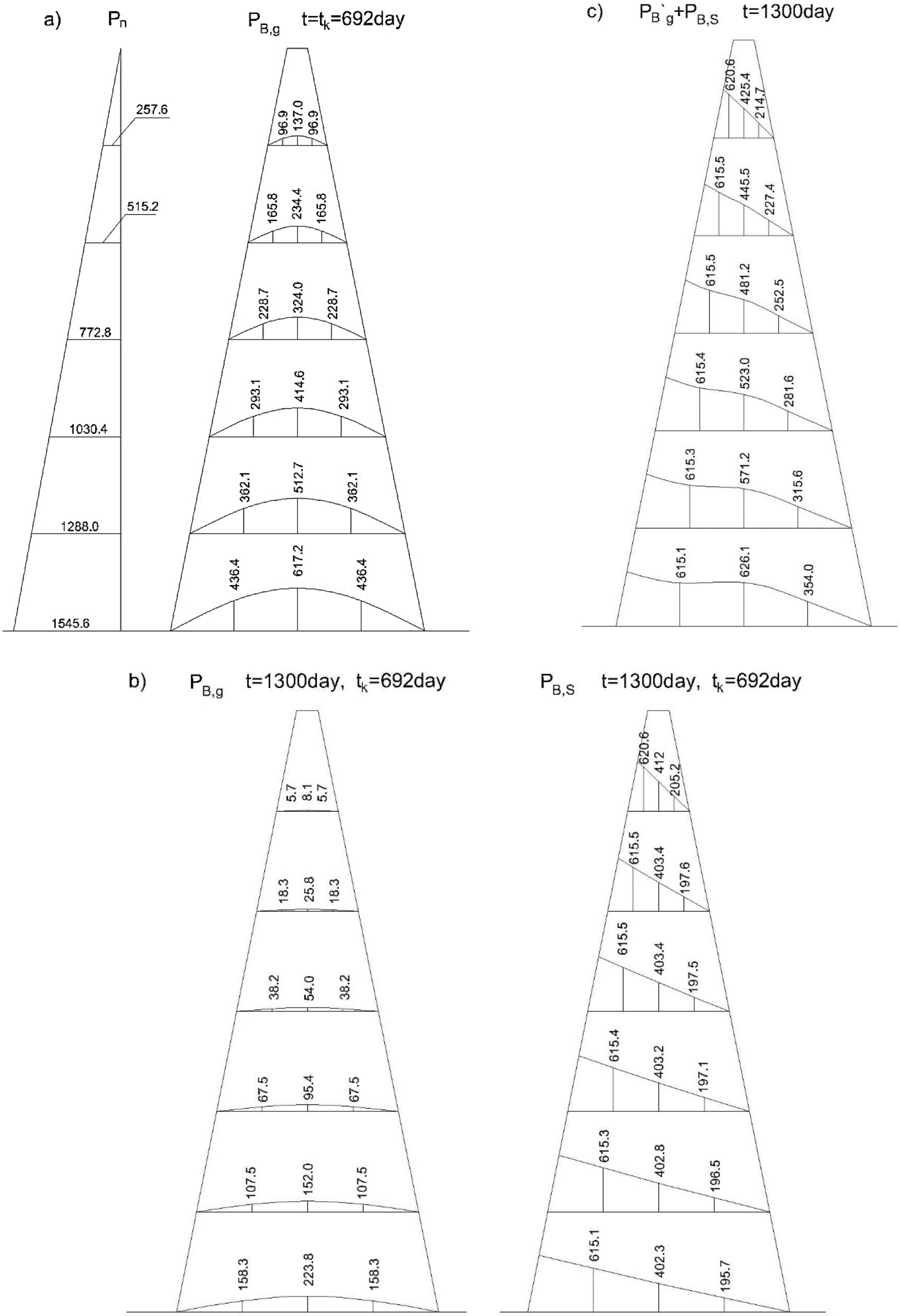

Fig. 2. The diagrams for porosity pressure
a - from own weight, b - from the rise of water level in reservoir,
c - from own weight and the rise of water level in reservoir

Conclusion

1. The calculation results show that the maximum porous pressure was obtained in the center of the base of the dam core. Immediately after the construction of the dam, it was 20% to 25% of the hydrostatic pressure, i.e. $P = (0,2...0,25)\gamma_0 H$.
2. The results of the calculation can be used to determine the stability of the dam core and slops, as well as to determine the deformation of the core and side prisms.

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