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RESEARCH OF HYDRAULIC AND STATIC WORK OF PRESSURIZED AND UNPRESSURIZED HYDROTECHNICAL TUNNELS

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Applicant: **Elchin Azer Pashayev**

AVTOREFERATION

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Scientific supervisor:	Doctor of philosophy in technical, Assosciate professor **A.A.Mursalov**
Official opponents:	Doctor of technical sciences **A.S.Mammadov**
	Doctor of Philosopy in technical, Assosciate professor **A.M.Muslumov**
	Doctor of Philosopy in technical **R.S.Abilov**

One-time Dissertation Council BFD 2.37, established on the basis of the Dissertation council FD 2.37 of Supreme Attestation Comission under the President of the Republic of Azerbaijan operating at the Azerbaijan University of Architecture and Construction

Chairman of the one-time Dissertation council:	Doctor of technical sciences, professor **Mukhlis Ahmed Hajiyev**
Scientific secretary of the one-time Dissertation council:	Doctor of philosophy in technical, associate professor **Maarif Zabit Yusifov**
Chairman of the one-time Scientific seminar:	Doctor of technical sciences, professor **Bahram Guseyn Alıyev**

GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic. Currently, in our republic, a wide area is given to the construction of tunnels for various purposes. Of these, transport, irrigation and water-conducting tunnels are most common. It was taken into account in the conditions of the Republic of Azerbaijan that hydrotechnical tunnels are underground engineering structures capable of transporting water over the shortest distance. The erosion, cavitation, and cracking phenomena occurring inside and in certain parts of tunnels create the need to reconsider their calculation methods. Since the occurrence of cavitation and erosion phenomena in tunnels is associated with vacuum, the prevention of these processes can be determined by determining the flow rate of air entering the tunnel and required. For this, new hydraulic calculation methods should be developed. Cracks in the upper arch of pressureless hydraulic tunnels and in the annular sections of pressure tunnels are due to errors made during the design or construction period. These errors may be due to the fact that the effects of existing loads and parameters are sometimes not taken into account. Since the dissertation work is devoted to solving these problems to some extent, the topic can be considered relevant.

Purpose of the work. The purpose of the dissertation work is to conduct the following scientific research:

- to obtain equations of motion to find the flow depths in various positions of the outlet of pressure hydraulic tunnels;
- to obtain the basic equations for the spatial state of the diagonal hydraulic jump in pressureless hydraulic tunnels, to determine the largest value of the difference in depths along the cross section based on the circulation constant assumed to depend on the angular velocity in the curved part of the tunnel;
- to determine the effect of air entering the unpressurized tunnel on the operating mode of the water flow;
- to find the required air flow rate into the tunnel as a result of a hydraulic jump event occurring behind the depth connector on the tunnel structures;

- to draw up calculation schemes for attaching first-type supports that can replace the effect of the external environment to pressurized and *unpressurized tunnels, and to find the final support reaction of the arch element of the unpressurized tunnel based on this scheme;*
- to develop a method for calculating the displacements and stability of an arch element, taking into account the effect of groundwater on a pressureless tunnel;
- to conditionally divide a tunnel with a circular cross-section into upper and lower semi-rings, and to determine the internal forces and check the stability of the annular section when the tunnel is empty and exposed to the hydrostatic pressure of water, taking into account the effect of groundwater on it;
- to solve numerical examples related to the proposed calculation methods and to determine the importance of applying these methods.

Scientific innovations. The scientific innovations in the dissertation work are as follows:

- using the law of change of the amount of movement, calculation formulas are obtained to find the depth resulting from the effect of the jump in the pressure sections of the tunnels at different exits, the pressure caused by the aero-flow at large drops, and the piezometric pressure at small drops;
- for the spatial case, when a diagonal hydraulic jump occurs in pressureless hydrotechnical tunnels, the interdependence equation of the associated depths is obtained, and in special cases encountered, this equation, solved by selection, falls into other forms;
- using the circulation constant adopted in the curved section of the pressureless tunnel, the flow rate and the difference in surface levels and the flow rate are determined;
- the self-aeration and local air entrainment costs entering the hydraulic jump zone behind the depth connector located on the tunnel through the air pipe, the cost of the air mass entrained in

the space above the surface of the aerated water flow are calculated using theoretically derived formulas;

- by replacing the effect of the external environment on the arch element of the pressureless tunnel by fixing the first type of supports, the final support reactions can be found using the new formula obtained by taking into account the loads falling on the tunnel;
- by taking into account the effect of groundwater on the arch section of the tunnel with an arched-rectangular cross-section, the internal forces are determined and it becomes possible to calculate the critical value of the longitudinal force;
- When the inside of a circular cross-section tunnel is empty and exposed to the hydrostatic effect of water pressure, the longitudinal and shear forces and bending moment in the upper and lower semi-circular sections can be found depending on the initial parameters, taking into account the pressure loads of the groundwater in the upper part, and the stability of these ring elements can be checked.

Practical significance of the work. The expressions obtained and the numerical examples solved in the dissertation work can be used in the relevant calculations not only of hydraulic tunnels, but also of transport and other purpose tunnels. It is possible to compare the results of the proposed calculation methods with the results of calculations of pipelines dug and placed horizontally and tunnels constructed according to existing standards, which indicates the practical significance of the work.

Reliability of the obtained results. The proposed calculation methods are based on the existing rules of hydraulics and classical mechanics and their laws of practical importance. The fact that the results of hydraulic calculations performed with theoretically obtained formulas and static calculations performed with modern computer programs are consistent and close to the results found by existing methods is the main indicator of the reliability of the obtained results.

Approval of the work. The results of the research conducted in the dissertation were reported and discussed at the XX Republican Scientific Conference of Doctoral Students and Young Researchers (Baku 2016), the Republican Scientific and Practical Conferences "Progressive Technologies in Modern Heating Equipment" (Baku 2017 and 2019), the scientific seminars of the "Land Reclamation and Water Management Construction" Department of the Azerbaijan University of Architecture and Construction (2016-2020), the International Scientific and Practical Conference "Energy-Saving Innovations in Architecture and Construction ESIAC2021" (Baku 2021), "Universum: Technical Sciences" (Moscow 2024), and the International Conference on Energy and Environmental Technologies in Engineering and Architecture" (Baku 2024).

Publication: The main results of the dissertation were published in six scientific articles (one (Published in the UK journal SAEQ in 2018).

The main issues presented for defense:

1. Study of hydraulic operating modes of pressurized and non-pressurized hydraulic tunnels.
2. Determination of the effect of air mass entering hydraulic tunnels on the operating mode of water flow.
3. Methodology for determining the required air mass flow rate to the tunnel through the aeration pipe when the flow is in pressurized and non-pressurized mode after the hydraulic jump occurring behind the depth connector placed on the tunnel structures.
4. Proposed calculation schemes for the effect of static loads on hydraulic tunnels located in elastic soil media and determination of support reactions for the arch element of non-pressure hydraulic tunnels based on these schemes.
5. Method for determining internal forces and longitudinal critical forces in the arch section of non-pressure hydraulic tunnels with arched-rectangular cross-section.

6. Methodology for calculating the effect of static loads on the upper and lower semi-rings (lateral arc ring elements) of circular cross-section hydraulic tunnels.
7. Analysis of the main indicators of hydraulic calculations performed for the exit part of pressurized tunnels and non-pressure tunnels.
8. Computer programs presented in algorithmic language for obtaining static calculations performed by the proposed methods for rectangular-arched and circular cross-section tunnels and their results.

The total volume of the dissertation is indicated by noting the volume of the structural sections of the dissertation separately. The total volume of the dissertation is 201058 characters (title 383 characters, table of contents 2910 characters, introduction 7182 characters, first chapter 42510 characters, second chapter 60045 characters, third chapter 46473 characters, fourth chapter 37358 characters, total the result is 4197 characters), 189 pages with 66 images, 17 tables and 108 literature list.

MAIN CONTENT OF THE WORK

The introduction justifies the relevance of the dissertation topic, indicates the purpose of the work, notes scientific innovations, practical significance, reliability of the results obtained and the issues raised for defense.

Chapter I consists of four subchapters and is devoted to the study of the structures of hydrotechnical tunnels and their existing calculation methods. The conditions for the application of hydrotechnical tunnels are noted, working conditions in pressurized and non-pressurized hydraulic modes are studied. The cross-sectional structures of tunnels encountered in engineering practice are shown, and the rules for selecting cross-sections are given, taking into account all their effects and determining in which hydraulic mode they will operate.

The hydraulic regimes of flow in hydrotechnical tunnels have been investigated based on the values of the Froude numbers. In numerous and different cases of movement in tunnels, regimes with pressure, without pressure, and both are observed in the flow along the tunnel. The state of the free surface of the without pressure flow in the tunnel is determined by the condition of immersion towards the downstream, which is an indicator that the value of the Froude number plays a key role. It has been noted that the following are characteristic cases based on the values of the Froude number:

1) the flow touches the upper wall at the entrance of the tunnel and at values of the Froud number $F_r < 0,1 \div 0,2$, the flow transitions to a single-pressure regime;
2) At values of Froude number $0,1 \div 0,2 \leq F_r < 1,0$, the observed wave process occurs as the flow in the tunnel falls on the free surface;
3) When the value of the Froude number varies in the interval $0,1 < F_r < 4,0$, and if there is no submergence in the flow from the downstream side, the edge of the wave generated on the surface extends towards the upstream side and touches the upper wall of the tunnel behind the vertical frosted aeration tube.

In the case where the outlet section of the tunnel is not immersed from the lower by-pass side, the flow through the tunnel increases in pressure, and at a certain distance from the inlet section, the flow breaks off from the wall surface with a pressure equal to the height of the tunnel and mixes with the flow in the lower by-pass. In finding the flow rate released from the construction tunnel with intermittent pressure hydraulic mode, the value of the depth behind the inlet section and the indicators of the free surface elevation curve play an important role. For this, it is shown that the outlet section of the tunnel is in a pressurized state. The reasons for the free surface of the intermittently changing pressure flow towards both the inlet and outlet sections of the tunnels are explained.

Considering that pressureless hydrotechnical tunnels have a rectangular arched cross-section, it is justified to allow longitudinal flow. Based on the determination of the flow rate of aerated flow passing through such tunnels, the necessity of finding the required air flow rate in the design process is noted.

It is given that the flow rate and the total pressure in front of the threshold of a tunnel device with a height of a operating in pressurized hydraulic mode are determined by the following well-known formulas, taking into account that the height of the location above the bottom level at the upper by-pass of the threshold is c:

$$Q = b\int_{-c}^{T} u_0 dz = bu_0\left(T + c\right) = b\int_{0}^{a} \upsilon da, \tag{1}$$

$$T_0 = \frac{1}{a}\int_{0}^{a}\left(z + \frac{p}{\gamma}\right)dz + \frac{\upsilon^2}{2\mu^2 g}, \tag{2}$$

where υ is the average velocity of the flow through the tunnel; μ is the flow coefficient:

$$\mu = \frac{1}{\sqrt{1 + \Sigma\xi}}. \tag{3}$$

Considering that the full edge width of rectangular-arched and circular cross-section tunnels is B_0 and the height is H0, the coverage distance of the cliff arch is found by the following well-known formula (Figure 1):

$$L = B_o + 2H_o tg\left(45^0 - \frac{\varphi}{2}\right) \tag{4}$$

For the standard loads acting on tunnels of such cross-section from above and from the sides, taking into account that the height of the overhang from the upper surface of the tunnel is h, the following known average values have been adopted:

$$q_n = \beta \gamma_q h\,, \tag{5}$$

$$e_n = \gamma_q \left(h + \frac{1}{2} H_o\right) tg^2\left(45^0 - \frac{\varphi}{2}\right), \tag{6}$$

where: β is the correction factor, and when $B_0<6,0\ m$, $\beta=0,7$ is taken, and when $B_0\geq 6,0\ m$, $\beta=1,0$ m is taken.

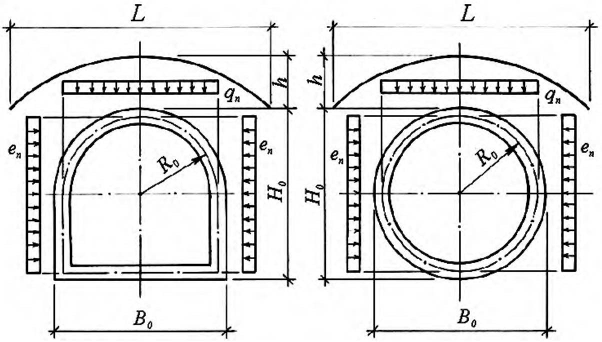

Figure 1. Existing calculation schemes for the effect of regular standard loads (q_n və e_n) on pressureless and pressured hydraulic tunnels.

According to construction norms and rules, when a circular tunnel ring with a central axis located at a height of hor above the ground is subjected to a constant external load, this load acts with an intensity of $q=\gamma h_{or}$ hor along the ring. When the ring of such tunnels is subjected to a load of varying intensity, the value of this load is assumed to be$\gamma_t(h_{or}–0,5D_x)$, at the top point of the tunnel, $\gamma_t h_{or} tg^2(45^0–\varphi/2)$ along the center line, and $\gamma_t(h_{or}+0,5D_x)$ at the lowest point.

New studies to be conducted on pressurized and non-pressurized hydrotechnical tunnels have been determined. The possibility of conducting the studies to be carried out in tunnels constructed at the Vaykhir hydrojunction on the Nakhchivanchay River has been noted.

In Chapter II, the hydraulic operating modes of pressurized and non-pressurized hydraulic tunnels were studied. The operating modes of pressurized culvert tunnels were studied and their hydraulic parameters were determined (Figure 2).

Using the equations of motion of the flow discharged from the tunnels into the downstream bypass in pressurized hydraulic mode the depth at the point where the downstream bypass touches the vertical wall of the tunnel exit after the hydraulic jump is calculated

$$h_n = \sqrt{\left(h_s^{''}\right)^2 + \frac{2q^2}{g}\left(\frac{1}{h_s^{''}} - \frac{1}{h_t}\right)} = \sqrt{\left(h_s^{''}\right)^2 - \frac{2q^2}{g}\cdot\frac{h_s^{''} - h_t}{h_s^{''}\cdot h_t}}, \tag{7}$$

the pressure of the air mass acting on the jet of water falling from a high-altitude step from the tunnel

$$h_a = \frac{2}{4\delta + h_t}\cdot\left[\frac{2q^2}{g}\cdot\frac{h_s^{''} - h_t}{h_t h_s^{''}} + \frac{h_t^2}{2} - \left(h_s^{''}\right)^2 + \delta_1^2\right], \tag{8}$$

piezometric pressure at a small height drop from the tunnel exit

$$h_0 = \frac{2}{4\delta + h_t}\cdot\left[\left(h_s^{''}\right)^2 - \delta^2 - \frac{h_t^2}{2} - \frac{2q^2}{g}\left(\frac{1}{h_t} - \frac{1}{h_s^{''}}\right)\right], \tag{9}$$

the calculation has been determined by the formulas.

The equation of flow velocity change was used in the outputs of formulas (7), (8) and (9). The dissertation explains the importance of applying these equations to cases of uneven distribution of flow in the transverse direction due to the influence of air mass in the lower bypass after large drops at the exit of tunnels with a flow rate exceeding 200 m^3/sec.

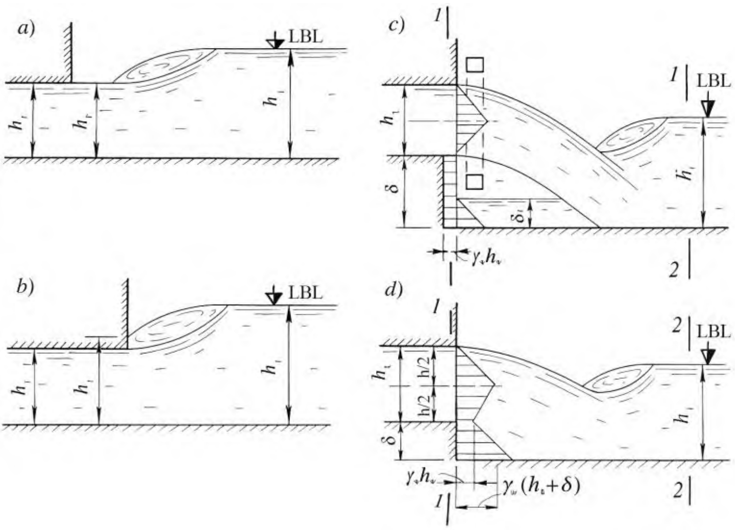

Figure 2. Level correlation diagrams at the exit from the pressurized tunnel to the lower by-pass:
a and b – when the flow is in non-submerged and submerged modes at the same level transition from the tunnel to the natural channel; c and d – when there is a drop at the transition from the tunnel to the natural channel, as is often the case.

The longitudinal cross-sectional structures of pressureless hydraulic tunnels are shown, their hydraulic working process is studied, and the irregularity of the movement is analyzed using a differential equation based on the value of the Froude number. The following equation was obtained to find the associated depths of the hydraulic jump in space in the obliquely curved section of pressureless tunnels (Fig. 3):

$$\begin{aligned} &h_2 \sin(\psi-\varphi)\left[h_1 h_2^2 \cos^2\beta_2 \sin(\psi-\varphi)\cos\varphi-\frac{2\alpha q_1^2}{g}\cos\beta_1 \sin\psi\right]= \\ &=h_1 \sin\psi\left[h_1^2 h_2 \cos^2\beta_1 \sin(\psi-\varphi)-\frac{2\alpha q_1^2}{g}\cos\beta_2 \sin\psi\cos\varphi\right], \end{aligned} \tag{10}$$

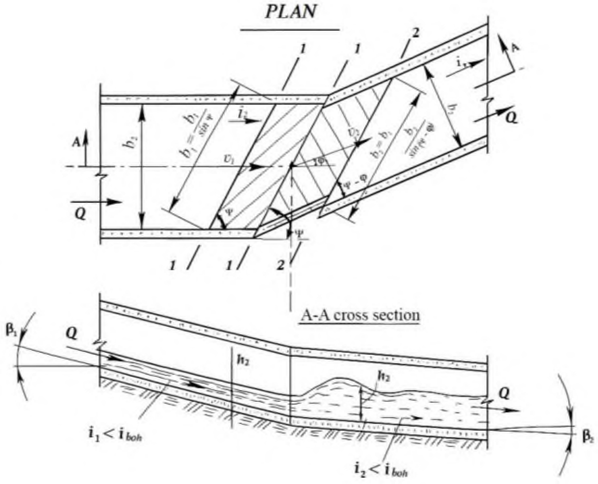

Figure 3. Calculation scheme for the hydraulic jump in undulating diagonals in pressureless hydraulic tunnels.

Based on the general expression (10), equations were obtained for the special cases encountered. Taking into account that the total specific energy of the flow in an arbitrary cross section of the curved section of a pressureless tunnel is $E_i = h_i + \frac{u_i^2}{2g}$ and assuming the circulation constant $k_s = \omega r^2$, the following formula was obtained to find the flow rate through the tunnel:

$$Q = k_s \cdot \ell n \frac{r_1}{r_2} \left(E_i - \frac{k_s^2}{2g r_1 r_2} \right). \tag{11}$$

In pressureless tunnels, the effect of the air above the flow was taken into account both in the irregular motion, in the basic differential equation, and in the determination of the hydraulic gradient. This air flow was taken in a state opposite to the direction of water flow along the tunnel. After finding the values of the flow modulus and Froude number, the role of these studies in determining the shape of the free surface and in determining the velocity of the air flow transmitted to the air space above the water through the aeration pipe ventilating the tunnels and returning from the downstream side was noted.

The effect of air entering hydrotechnical tunnels on the operating mode of the water flow was studied, and the main equations of the pressureless and pressured modes of hydraulic jump behind the depth seal were obtained. The flow rate Q_a of air entering the tunnel from the aeration pipe is divided into the flow rates of local trapping ($Q_{\square}$) of the air flow in the wedge section behind the threshold of the seal chamber, self-aeration ($Q_{a\omega}$) mixing with the water flow from the free surface in the form of bubbles, and the air flow (Q_{as}) moving in the space above the water flow surface along the length of the tunnel is depicted in Figure 4:

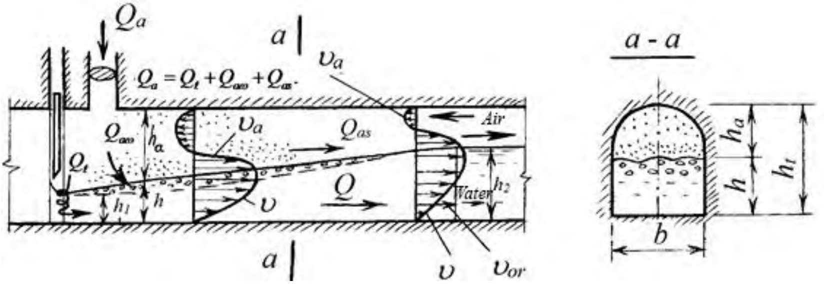

Figure 4. Hydraulic calculation scheme for water flow with a smooth riser curve behind the seal in unpressurized tunnels, taking into account the effect of air flows.

Considering that the air and water flow rates vary with depth according to the binomial and trinomial quadratic parabola laws, the self-aeration flow rate can be calculated based on the known flow rate Q of water passed through the tunnel

$$Q_{a\omega} = \frac{\alpha b h}{6h_m\left(h - h_m\right)} \cdot \left[2\left(\upsilon_s h_m - \upsilon_{\max} h\right)h + 3\left(\upsilon_{\max} h^2 - \upsilon_s h_m^2\right)\right] - Q, \quad (12)$$

and the drag air flow rate in the surface space

$$Q_{as} = \alpha_q b \int_{h}^{h+h_a} \upsilon_a dz = \alpha_q b \upsilon_s \left\{ \frac{1}{h_a h_{ak}} \cdot \left[\frac{1}{3}\left(h_a^3 + 3h^2 h_a + 3hh_a^2\right) - \right.\right.$$

$$\left.\left. -\frac{1}{2}\left(h_{ak} + 2h + h_a\right)\left(h_a^2 + 2hh_a\right) + hh_a\left(h_{ak} + h + h_a\right) \right] + h_a \right\} \qquad (13)$$

the calculation with the formulas is given in the dissertation.

When the air flow entering the tunnel is separated into self-aeration and surface entrainment flows (Figure 5), the following formula was used to find this flow [1]:

$$Q_a = Q_{a\omega} + Q_{as} = \frac{\alpha b h''_{sa}}{h_m\left(h''_{sa} - h_m\right)} \cdot \left\{ \frac{1}{3}\left(\upsilon_{sa} h_m - \upsilon_m h''_{sa}\right) h''_{sa} + \right.$$

$$\left. + \frac{1}{2}\left[\upsilon_m \left(h''_{sa}\right)^2 - \upsilon_{sa} h_m^2\right] \right\} + \alpha_q b \left\{ \frac{1}{h_a} \cdot \left[\left(h''_{sa}\right)^2 + h_a\left(h''_{sa} + \frac{1}{3}h_a\right) - \right.\right. \qquad (14)$$

$$\left.\left. -\left(h''_{sa} + h_a\right)\left(h_a + 2h''_{sa}\right) + h''_{sa}\left(2h_a + h''_{sa}\right) \right] + h_a \right\} \upsilon_{as} - Q.$$

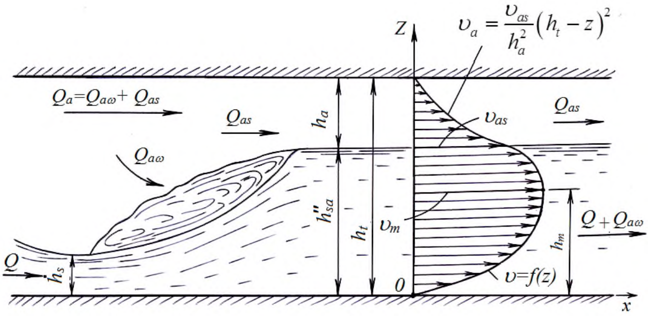

Figure 5. Scheme for determining aeration flow rate (Q_a) based on the velocity profile of air and water flow in tunnels operating in pressureless mode after hydraulic jump.

In tunnels where depth connectors are installed, the equation of the aeration flow velocity was written, taking into account the effect of the vacuum pressure at the final section of the hydraulic jump formed after the connector.

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[1] Mursalov, A.A., Pashayev, E.A. Determination of the air flow rate entering the aeration pipe during the hydraulic jump after the depth connectors in hydrotechnical tunnels // –Baku: “Ecology and Water Management” Scientific-Technical and Production Journal, –2018. №5 (71), –p. 57-60.

From this equation, it was possible to find the piezometric pressure above the upper wall of the mentioned tunnel[2]. Determining this pressure allowed us to determine both the depth of the flow in the lower by-pass and the state of the piezometric pressure line falling along the tunnel after the jump, for the case where the tunnel exit ports operate in submerged hydraulic mode. This process was reflected in the dissertation with a calculation scheme.

After a hydraulic jump event occurring behind a depth connector placed in the tunnel, the flow passes through the tunnel in a pressurized hydraulic mode. The piezometric pressure at the final section of the jump was determined, the required air flow rate was found, and the necessary calculation formula was obtained to determine the internal diameter of the aeration pipe depending on the water flow rate transmitted through the tunnel.

In Chapter III, the methods of calculating the effects of static loads on hydraulic tunnels were developed. Calculation schemes for these tunnels against the effects of these loads were drawn up and by applying type 1 reaction supports that can withstand the load effect on the arch element of the pressureless tunnel, the support reactions at the junction of the arch with the rectangular element were found.

Calculation schemes for the static effects of the arch were applied according to the conditions of fastening the arch and rectangular parts of the arched-rectangular cross-section tunnels. Taking into account the loads falling on the arch element from the cliff arch of the soil surrounding it, the reaction forces from the tunnel side wall elements to the arch element were determined using the loads written according to the equilibrium conditions of statistics. These expressions of the support reactions allowed us to find the longitudinal and shear forces in an arbitrary section of the arch element. The final expression of the load falling irregularly on the tunnel arch was obtained from the mentioned effects.

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[2] Mursalov, A.A., Hasanov E.E., Pashayev, E.A. The influence of air (entering into closed water conductor facilities) on working rejime of water flow // – England: Journal «SAEQ» science at applied engineering quarterly, –2018. issue 15, –pp. 8-10.

In the developed calculation scheme (Fig. 6), the effect of this load was replaced by a force directed towards the arch in radial directions by integrating within the boundaries of the coverage angle up to the considered section. The differential equations of the elastic axis of the tunnel arch elements in bending, taking into account the effect of groundwater, are expressed as follows:

$$\frac{d^2w}{d\theta^2}+w=-\frac{MR_0^2}{EJ}; \qquad \frac{du}{d\theta}-w=0. \tag{15}$$

By integrating equations (15), the vertical and horizontal displacements of an arbitrary section of the arch were determined. The following formulas were obtained to find the bending moment and longitudinal force in the section located at an angle θ with respect to the central axis of the tunnel (Fig. 6):

$$\begin{gathered} M_\theta = M_0' tQ_0u_0 + \left(N_0 + bR_0q_0\right)\left(R_0 - w_0\right) + Q_0R_0\sin\theta - \\ -N_0R_0\cos\theta + bR_0q\left(\theta\right)\left(u_0\sin\theta + w_0\cos\theta\right). \end{gathered} \tag{16}$$

$$\begin{gathered} N_\theta = -V_R\sin\theta - H_R\cos\theta - bR_o\sin\left(\frac{\pi}{4}-\frac{\theta}{2}\right)\left\{\gamma_w\left[\left(h_o+R_x\right)\times\right.\right. \\ \left.\times\left(\frac{\pi}{2}-\theta\right)-R_x\cdot\cos\theta\right]+\left[\gamma_1\left(H_o-h_o\right)+\gamma_2\left(h_o+R_x\right)\right]\cos\theta - \\ -\frac{1}{2}\gamma_2R_x\left(\frac{\pi}{2}-\theta+\frac{1}{2}\sin2\theta\right)+\gamma_2tg^2\left(45^0-\frac{\varphi_2}{2}\right)\times \\ \left.\times\left[\left(h_{ek.}+h_o+R_x\right)\left(1-\sin\theta\right)-\frac{1}{2}R_x\cos^2\theta\right]\Bigg]\right\}, \end{gathered} \tag{17}$$

where: M_0' Q_0, N_0, q_0, w_0, u_0 – are the bending moment, shear force, longitudinal force, load intensity value, and displacements in the vertical and horizontal directions, respectively, in the section along the centerline of the tunnel due to the action of external loads.

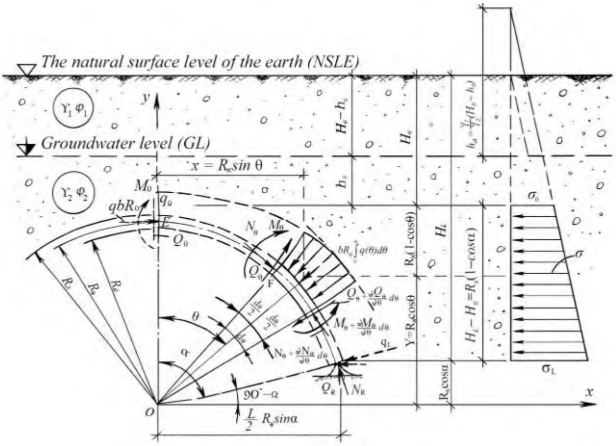


Figure 6. Calculation scheme for the effect of static loads on the arch section of pressureless hydraulic tunnels.

In the equations written for the case of loss of stability of the arch element to the side walls due to symmetrical loading, the determinant, which is made up of the coefficients of the initial unknown parameters (shear force and bending moment), is taken equal to zero. The equation obtained by opening the determinant can be solved selectively or graphically, which allows finding the critical values of the longitudinal and shear forces, which are an essential condition for stability. These issues were considered in the versions of the arch element of the tunnel with and without a semicircle. For the case of a rigidly connected arch element to the side walls, the necessary expression of the bending moment at that connection section was obtained as the support reaction.

The method for calculating the bending (displacement) of the ring elements, taking into account the effect of static loads, including groundwater, of hydraulic tunnels with a circular cross section, has not been developed (Fig. 7).

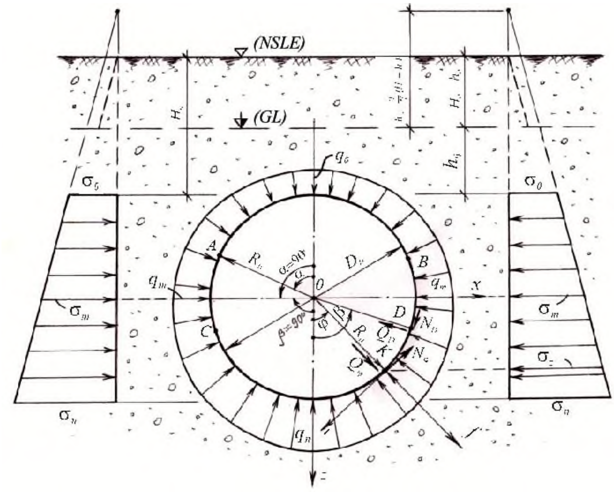


Figure 7. Scheme for determining static loads acting on a circular tunnel along a full annular cross-section.

The tunnel is divided into top, side and bottom elements to allow for calculation of static effects along its entire circumference. Considering the bulk density of the soil surrounding the tunnel as φ_2, the angle of internal friction as γ_2, the stiffness index as m_2 and the settlement of the tunnel ring as wc during the service life, the final static load acting on the tunnel is expressed as follows:

$$q_\varphi = \gamma_w\left[h_0 + R_0\left(1+\cos\varphi\right)\right] + \gamma_2 tg^2\left(45^0 - \frac{\varphi_2}{2}\right) + \left[h_{ek} + h_0 + \right.$$
$$\left. + R_0\left(1+\cos\varphi\right)\right]\sin\varphi + m_2 w_c\left[h_{ek} + h_o + R_o\left(1+\cos\varphi\right)\right]\cos\varphi. \qquad (18)$$

The support reaction at the junction C or D of the tunnel ring is determined by the following formula:

$$N_D = \frac{bR_o}{2\sin\frac{\beta}{2}}\left\{\gamma_w\left[\left(h_o + R_o\right)\beta + R_o\sin\beta\right] + \gamma_2 tg^2\left(45^0 - \frac{\varphi_2}{2}\right)\times\right.$$

$$\times\left[2\left(h_{ek} + h_o + R_o\right)\sin^2\frac{\beta}{2} + \frac{1}{2}R_o\cdot\sin^2\beta\right] + \qquad (19)$$

$$\left. + m_2 w_c\left[\left(h_{ek} + h_o + R_o\right)\sin\beta + \frac{1}{2}R_o\left(\beta + \frac{1}{2}\sin 2\beta\right)\right]\right]\Bigg\}.$$

After finding the support reaction at the fastening points of the tunnel semi-rings along the horizontal central axis, the necessary formula was obtained to find the stable settlement of the tunnel during the operation period under the influence of existing loads, which allowed to build a diagram of the impact load arising from the reactive resistance of the soil on the sub-semi-ring. As in pressureless hydraulic tunnels, expressions for bending moment, longitudinal and shear forces were obtained in an arbitrary cross-section of the upper and lower semi-rings of circular-shaped tunnels with annular cross-section. Also, when the circular-shaped tunnel ring is divided into upper, lower and side rings, these issues were solved. This methodology allows to calculate the stability and strength of the tunnel ring both in tension and compression.

The following trigonometric equation was derived to check the stability and strength of the tunnel ring:

$$\left[\sin\varphi_{b\ddot{o}h.} + \frac{1}{\sigma k_n^2}\left(1 - \frac{w_n}{R_o}\right)\left(1 - k_n^2\right)\varphi_{b\ddot{o}h.}^3\right] tg\varphi_{b\ddot{o}h.} + 2\sin^2\frac{\varphi_{b\ddot{o}h.}}{2} = 0. \qquad (20)$$

It is explained in the dissertation that by finding $\varphi_{b\ddot{o}h.}$ from equation (20) selectively or graphically and substituting its value into the expressions for longitudinal and shear forces, their critical values can be determined.

Chapter IV is devoted to the solution of numerical examples related to the proposed hydraulic and static calculation methods of hydrotechnical tunnels. With the conducted hydraulic calculations, velocity diagrams of air and aerated water flow inside the tunnel were constructed (Fig. 8; 9 and 10).

A computer program was developed in algorithmic language for the calculation of arch elements of rectangular-arched tunnels for static effects, and diagrams of bending moment, shear and longitudinal forces were constructed (Fig. 11).

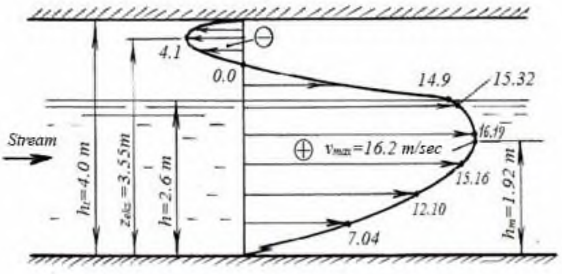


Figure 8. Velocity plot of air and water flows changing direction in a pressureless tunnel

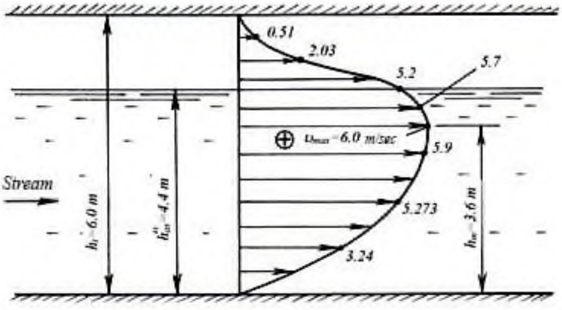


Figure 9. Velocity plot of co-directional air and aerated water flow

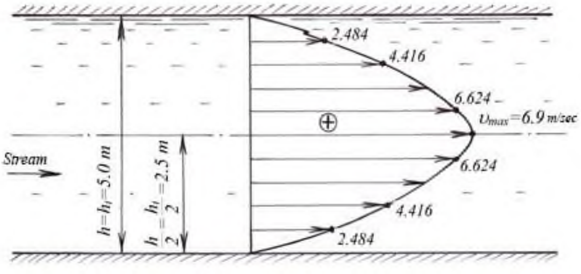
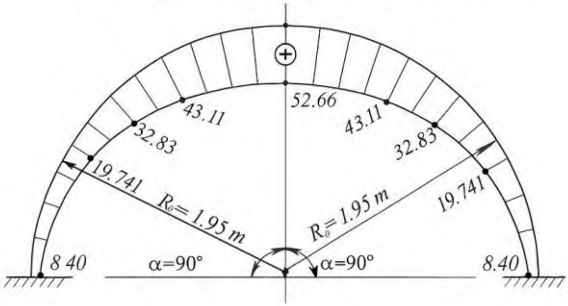
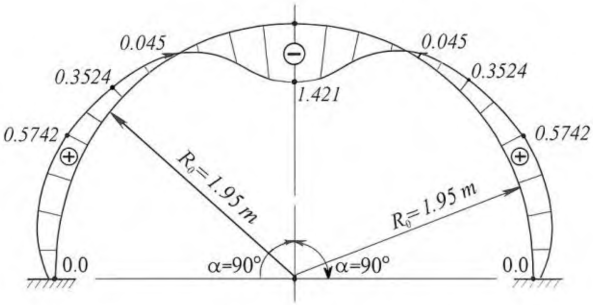


Figure 10. Velocity diagram of an aerated flow passing through a tunnel in a pressurized mode

Bending torque curve (M_0), with t.gr.m.



Cutting force (Q_0), with t.gr.



Longitudinal force curve (N_0), with t.gr.

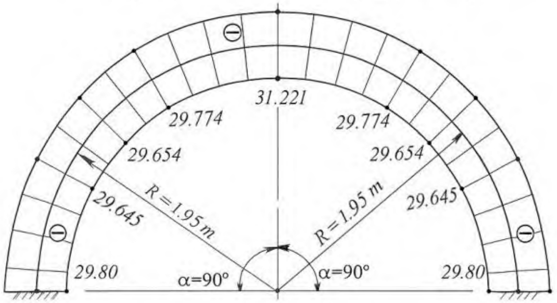


Figure 11. Diagrams of internal forces in the arch element of a rectangular cross-section tunnel (on the example of the tunnel of the suburakhan facility of the Vaykhir hydroelectric junction).

RESULTS

The main results obtained in the dissertation work are as follows:

1. In the case of hydraulic jumps at the exit of pressurized hydraulic tunnels, when they are far away and submerged, and in the case of large and small single-step drops from the tunnel, the necessary expressions for determining the required depths and pressures of the flow have been obtained using the law of change of the amount of movement.
2. In unpressurized tunnels, when a diagonal hydraulic jump occurs in space, based on the conditions of equality of the changes in the amount of movement and the force impulse in the diagonally curved zone of the tunnel, the dependence equation between the associated depths of the flow before and after the jump has been obtained, and this equation has been analyzed for all the special cases encountered.
3. By assuming a circulation constant in the curved section of a pressureless hydraulic tunnel, new theoretical formulas were obtained by hydraulic methods to find the change in water levels and the flow rate through the tunnel depending on the radii of the location of the outer vertical lines along the cross section of the flow, which can be considered very important for the design process.
4. The effect of air entering hydraulic tunnels on the hydraulic operating mode of water flow in various conditions was studied, and the basic differential equation of irregular motion was analyzed for practical problems encountered in pressureless tunnel-type water culverts depending on the piezometric slope of the aerated flow, the velocity-pressure slope of the returning air flow in the surface space, and the Froude number of the flow in any section.

5. Assuming that the velocity of the aerated water and air flow above it behind the depth connector placed on the tunnel changes according to a parabolic law, new calculation formulas have been obtained to find the local trapping of air entering the tunnel in the pressureless hydraulic flow along the length of the device, self-aeration, and the entrained air flow on the aerated water flow.
6. Expressions have been obtained to theoretically determine the piezometric pressure of the pressurized flow above the inner surface of the upper wall of the tunnel and the air flow entering the tunnel after the hydraulic jump occurring behind the depth connector designed on the tunnel route.
7. Calculation schemes for the effect of static loads in elastic soil environments of pressurized and pressureless hydrotechnical tunnels have been developed.
8. By replacing the effect of the external environment on the arch part of unpressurized hydraulic tunnels with type 1 supports, a calculation formula was obtained for determining the support reaction forces under the influence of static loads.
9. A method for calculating the displacements, internal forces and stability of the arch element of tunnels with arched-rectangular cross-sections under the influence of static loads, taking into account the effect of groundwater on them, was developed.
10. In cases where the effect of water pressure inside hydraulic tunnels with circular cross-sections is not taken into account and is taken into account, a calculation methodology for the effect of static loads by dividing its ring section into upper, lower and side elements has been proposed.
11. Numerical examples were solved using the proposed methods and hydraulic parameters were determined at the exit of pressurized hydraulic tunnels.

12. By performing hydraulic calculations in hydraulically pressurized tunnels with oblique and circular bends, the corresponding depths of the hydraulic jump were found, and the difference between the proposed and existing water levels in the cross section of the tunnel bend was found to be quite close to each other. It was also explained that the flow velocities at the beginning of the bend section, found by the formulas of theoretical and experimental methods, were close to each other.
13. Based on the characteristic values of the flow velocity recorded as a result of measurements after the hydraulic jump occurred behind the connector placed on the tunnel device, the local entrapment, self-aeration, and entrained air flow rates entering the tunnel were calculated, and joint diagrams of aerated water and air flow velocities were constructed in three cases encountered along the height of the tunnel.
14. The arch element in the tunnel of the irrigation facility of the Vaykhir hydroelectric power station, among the rectangular-arched cross-section hydrotechnical tunnels, was calculated for static effects, and diagrams were constructed based on the values of internal forces found with a modern computer program.
15. The circular cross-section irrigation tunnel to the SES in the derivation tract on the right bank of the Khudaferin hydroelectric power station was divided into upper and lower semi-rings and static calculations were carried out using the proposed methodology. When the tunnel is empty and exposed to the hydrostatic pressure of water, diagrams of the final load, longitudinal and shear forces, and bending moment were constructed, and comparative analyses were conducted.

List of published scientific works on the topic of the dissertation work

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13. Mursalov, A.A., Hasanov E.E., Pashayev, E.A. The influence of air (entering into closed water conductor facilities) on working rejime of water flow // – England: Journal «SAEQ» science at applied engineering quarterly, –2018. issue 15, –pp. 8-10.

Claimant's personal contribution in printed works:

[1, 4, 8-10, 12] - scientific works were carried out independently by the author.

[2, 3, 5-7, 11, 13] - in scientific works, the solution of the problem, analysis of the collected data, and conducting experiments were carried out by the author, while the formulation of the problem and the processing of the obtained results were carried out jointly with the co-authors.

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