ECONOMICOMATHEMATICAL MODELS FOR SELECTING CRACK-RESISTANT LININGS FOR HYDRAULIC PRESSURE TUNNELS

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At the stage of technicoeconomic substantiation when designing hydrodevelopments the makeup of structures, including long tunnels, is selected. The need arises to establish an economic type of lining for pressure tunnels of various dimensions for different geologic conditions and different heads of water. The same need arises also when making static calculations of tunnel linings at later design stages, when the initial data (including the type and thickness of the linings) are selected for computer calculations. This article offers recommendations for facilitating selection of the lining parameters for circular pressure tunnels.

It is recommended to select the type of linings for specific conditions by using the economicomathematical models proposed here. As the optimality criterion we use the cost (S) per running meter of tunnel of the four most used types of lining: single-layer (concrete or reinforced concrete) and double-layer (with inside reinforced Gunite or steel shells). The cost of a running meter of tunnel includes the cost of driving the tunnel and constructing the lining, which usually amounts to about 90% of the total cost of tunnel construction according to Chapter 2 of the Estimated Financial Computation, with overhead costs amounting to 26.8% and average cost of operating processes, adopted for installations of the State All-Union Trust for Stabilization of Foundations and Structures (Gidrospetsstroi), amounting to 25% of the cost of the main work. The least value of S represents the most economic type of crack-resistant lining for a pressure tunnel.

The economicomathematical model takes into account three main factors for selecting the pressure-tunnel lining, which the designer usually has on hand at the technicoeconomic substantiation stage: internal hydrostatic pressure, inside tunnel cross section, and characteristics of the rocks. For each type of lining its thickness was established by calculations based on various values of these factors, then the cost per running meter was calculated on the basis of the volume of work and its cost. A statistical analysis of the results made it possible to create an economicomathematical model for each type of lining.

The thicknesses of the tunnel linings were established for conditions of crack resistance to internal water pressure during operation and checked for loads from the rock pressure and the lining's weight (period of construction and emptying of the tunnel). The calculations were made in conformity with the "Instructions for the Design of Hydraulic Tunnels" (Construction Specifications SN 238-73) by the limit design method for the case where the depth of the tunnel was more than three inside diameters and the internal water pressure was balanced by the weight of the rocks above the tunnel.

The lining materials were those most often used in underground construction: concrete and reinforced concrete grade 250 (Rc = 18 kgf/cm², Ec = 2.9·10⁵ kgf/cm²); Gunite grade 500 (Rc = 35 kgf/cm², Eg = 3.0·10⁵ kgf/cm²); 09G2 steel for the inside shell (Rc = 3000 kgf/cm², E = 2.1·10⁵ kgf/cm²) and class A-II reinforcement (Rc = 2700 kgf/cm²). If the formulas from SN 238-73 for calculating a lining crack-resistant to the internal pressure are transformed with consideration of the standard and calculated characteristics of the strength of these materials, that lining thickness can be determined by the following relations:

a) by Eq. (30) from SN 238-73 for a concrete lining

\[ h_c = r(0.0926 \cdot p - 0.000493 \cdot k_0) \]

for a reinforced-concrete lining in rocks with a strength coefficient f_str < 4
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Fig. 1. Range of minimum design thickness ($h_c = 20$ cm) of a concrete lining of a free-flow tunnel.

Fig. 2. Range of minimum design thickness ($h_{r-c} = 20$ cm) of a reinforced-concrete lining of a free-flow tunnel.

in rocks with $f_{str} \geq 4$

for a reinforced Gunite shell

$B$ by Eqs. (16), (17), (22), (24), and (25) from SN 238-73 for a metal shell

In the equations the thicknesses of the linings are in centimeters; $p$ is the internal water pressure, kgf/cm²; $k_o$ is the coefficient of specific passive rock pressure, kgf/cm³; $r$ is the inside radius of the lining, cm.

The need to resist the rock pressure and other loads during construction or repair of the tunnel and the lining during construction limits the minimum thickness of the pressure-tunnel lining, both single-layer and the outer ring of the double-layer lining with an inside reinforced-Gunite shell to not less than 20 cm. Therefore, the linings of a pressure tunnel are checked also for loads acting during emptying of the tunnel, namely: the rock pressure and the lining's own weight (the groundwater pressure was not taken into account). The forces in the lining were determined by the method developed by O. E. Bugaeva (Technical Specifications (TU) 11-58) and the cross sections were verified according to Construction Norms and Specifications (SNiP) II-1.14-69.

Thus for each type of lining, depending on the variables $D$ (inside diameter, m) and $k_o$ we obtained a certain set of numbers for the lining thicknesses which was regarded as a conditional distribution function, and the form of the relation was selected for constructing the statistical model. The method proposed earlier [1] was used for solving this problem on a computer.

The statistical models were represented in linear form

$$y = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_p x_p$$

By statistical treatment of the initial data it was found that the thicknesses of concrete and reinforced-concrete linings of circular tunnels operating during the emptying period (a limitation of the minimum thickness of a pressure-tunnel lining) can be determined by the following equations:

$$h_c = 0.25 - 0.00206 k_o + 0.06585 D + 0.27 \times 10^{-4} k_t + 0.00148 D^2 + 0.724 \times 10^{-4} D k_o;$$

$$h_{r-c} = 0.306 - 0.00213 k_o + 0.012 D + 0.346 \times 10^{-4} k_t + 0.00129 D^2 - 0.649 \times 10^{-4} D k_o.$$