

Flow modelling, tracer methods, and hydrometric tests in the River Vah basin, Slovak Republic

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Abstract Fifty-four reservoirs have been built in the basin of the River Vah, Slovak Republic, over various geological formations. The reservoirs are used for flood protection, drinking water supply, and hydroelectric power. The grouting curtains were a serious problem during dam construction. Maximum seepage was estimated for the Liptovská Mara and Turcek dams and ranged between 0.060 and 0.070 m³ s⁻¹. The real seepage, and implications for the subsoil stability were questionable. Borehole tracer methods were used to address this problem. The results show that maximum real seepage was 0.030 m³ s⁻¹, and filtration velocities have never reached critical values for the filtration stability of fine fills in rock fissures or gravel pores.

INTRODUCTION

The upper part of the Vah basin is characterized by rocks of Carpathian flysch composed of layers of sandstones and claystone. The largest reservoir, Liptovská Mara (Fig. 1), was constructed on this geology. In a smaller part of the Vah basin are volcanic rocks such as andesites and their tuff agglomerates. The Turcek dam was constructed here.

Gravel soils underlie the dams. These drain the groundwater from the slopes as well as the seepage water from the dam.

A brief summary of the tracer methods, and their practical applications are given in this paper. The main objective of the paper is to quantify the efficiency of the grouting curtains.

Single borehole tracer methods had been used on the sites of both dams prior to flooding of the reservoirs. These techniques permit the quantification of groundwater flows and seepage. Layers of greater hydraulic conductivity were identified during grouting. During reservoir filling, tracer methods were used to study local anomalies. Tracer methods may also be used during reservoir operation to monitor the development of seepage over time.

The dam body and subsoil seepage account for about 30% of dam defects, dam accidents and dam breakdowns (Sherard, 1966); thus these conditions are given special attention in the Slovakian dams.

TRACER METHODS

The International Atomic Energy Agency's regular conferences on radioactive substances in hydrology, as well as the IAHS International Committee on Tracers

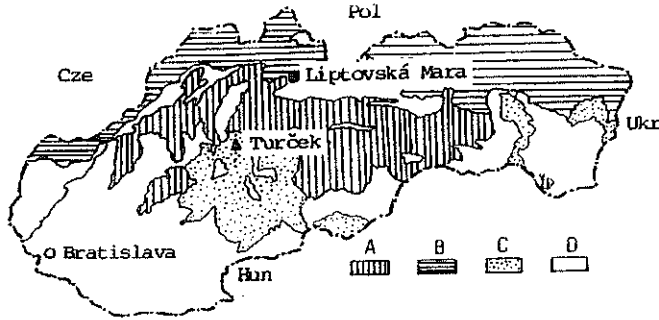


Fig. 1 Geological map of Slovakia (Matula, 1965): A—core mountains, B—Carpathian flysch, C—neogenous founders, D—neogenous tectonic depressions, and location of studied dams in the Váh basin.

provide an important contribution to the development of tracer methods. In the Slovak Republic, single borehole methods have been developed from Halevy *et al.* (1967), whereby tracer dilution and vertical migration are monitored.

Artificial radioactive solutions can be traced by bromine (^{82}Br), iodine (^{131}I) and other radionuclides. These tracers have the advantage that when there is no difference between the tracer temperature and the water temperature, they mimic natural water flow. However, radioactive substances are difficult to obtain in the Slovak Republic due to health and safety concerns. Therefore we used sodium chloride to trace groundwater flows.

A portable conductivity probe was used to monitor the dilution of the tracer in a single borehole. Filtration velocity v_{fi} in the monitored depths of the borehole is estimated by the formula:

$$v_{fi} = \frac{\pi d}{4\alpha t} \ln \frac{c_o - c_p}{c - c_p} \quad (1)$$

where d is the observation borehole inner diameter; α is the borehole drainage influence coefficient ($\cong 2$); c_o is the initial concentration; c is the concentration in time t ; c_p is the background concentration.

Filtration velocity can range between 10^{-7} and 10^{-3} m s^{-1} ; as a result accuracy is influenced especially by vertical water flow in the borehole and density solution flow. Therefore special measuring equipment with a sealed dilution volume minimizing the main spurious factors (e.g. Drost, 1970) is used.

The average value for the height of the water column is calculated by the formula:

$$v_f = \sum v_{fi} \Delta h_i / \sum \Delta h_i \quad (2)$$

(Δh_i is the depth increment with the value v_{fi}) and is usually depicted as a vector. It can be also used for discharge calculations based on the continuity equation.

Permeability coefficients are calculated from Darcy's law using the hydraulic gradient values from the surrounding.

For vertical water flow in boreholes an immersion probe is used with pneumatic-hydraulic jetting dosage equipment and two conductivity meters fitted above and below the jetting place at a distance of 0.5 m. The immersion probe is connected to the computer transducer with a cable and then to a portable computer. Concentration

curves can be seen directly on the computer screen as well as flow direction and time for the following calculations.

From the vertical water flow measurement in the borehole, the value of water flow filtration velocity in the surrounding medium (approximately in the horizontal direction) is calculated by the formula:

$$v_{\beta} = \frac{\Delta q_v}{\bar{\alpha} d \Delta h} \quad (3)$$

Δq_v is the vertical flow increase or decrease in the part with height Δh ; $\bar{\alpha} \cong 20$ is the vertical flow borehole drainage influence coefficient; d is the inner diameter of the observation borehole.

More problems connected with artificial or natural affects or tasks connected with time development can be solved based on changes of vertical discharge q_v or specific vertical discharge $\Delta q_v / \Delta h$.

The approaches mentioned enable the researcher to monitor "natural" water flow in boreholes due to interconnection of different pressure horizons, but they also enable the monitoring of vertical flow caused by artificial influences such as pumping or water introduction into boreholes.

SEEPAGE MONITORING UNDER THE LIPTOVSKA MARA DAM

The cross-section of the Liptovská Mara rockfill dam (Fig. 2), shows observation boreholes for groundwater and seepage monitoring in the Quaternary and Palaeogenous subsoil. They have been built into the grouting curtain and natural fissure medium under it. The fact that the rock strata at bottom of the dam slope at the angle of 20° together with other factors were the reasons for a design of an especially short grouting curtain. Further, the curtain was being finished during reservoir filling and operation until 1990. The bottom drainage was placed relatively high and very permeable gravel soils in the dam subsoil manage to drain the seepage water in such a way that its table never reaches the bottom drainage. Seepage amounts and hydrodynamic effects under this dam can be monitored by single borehole tracer methods only.

The average filtration velocity in the gravel subsoil of the dam in 1998 calculated from equations (1), (2) and (3) are illustrated in Fig. 3. Flows in 1998 (full lines) were very different to those in 1975 (dashed lines).

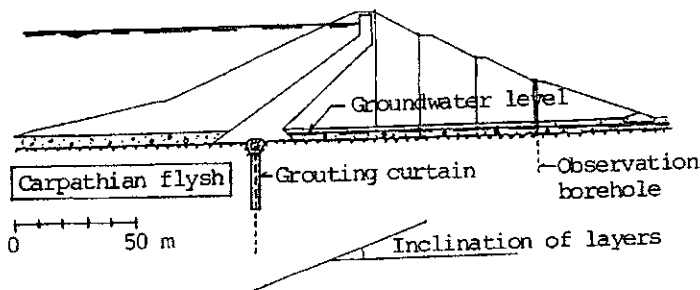


Fig. 2 Cross-section of the Liptovská Mara dam.

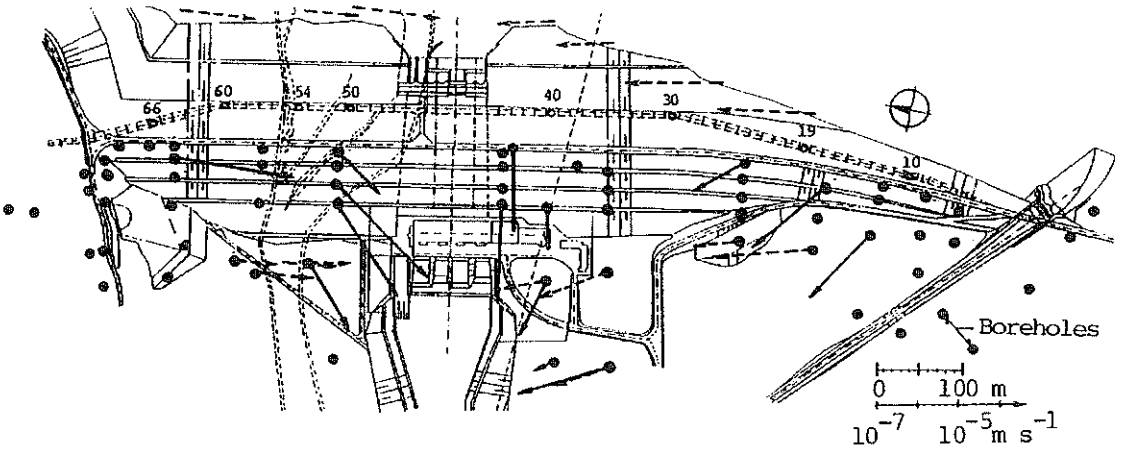


Fig. 3 Average filtration velocity vectors: - - - - for the empty reservoir in 1975, ——— for the full reservoir in 1998; Observation boreholes for the single borehole tracer method are numbered 10, 19, 30, ..., 66.

In the valley part of the dam the flow changed about 90° and also the seepage from the side slopes is concentrated into it. The water table below the dam rose by about 1.5 m following flooding of the reservoir.

The increased seepage volumes are the result of two key components: the increase in the filtration velocity and the rise in the water table. Currently seepage is about $0.020 \text{ m}^3 \text{ s}^{-1}$. There were not many modern calculation methods available when during the design phase in 1970; classical calculations gave assumed seepage of about $0.070 \text{ m}^3 \text{ s}^{-1}$.

Since maximum filtration velocities have never reached critical values for the filtration stability (Ronzhin, 1974), hydrodynamic effect and stability analyses ceased.

The tracing data revealed a further implication. It was shown that the performance of the grouting curtain was adequate, even though pressure tests conducted during construction indicated that the sealing criteria were not satisfied (Kutzner, 1985; Verfel, 1983). At 10 m below the grouting gallery, the criteria were not fulfilled for about 30% of the pressure tests. This suggests that water pressure tests are not suitable for grouting curtain efficiency control especially when such tests are done at a higher table in the reservoir.

MODELLED AND REAL SEEPAGE UNDER THE TURCEK DAM

The rockfill Turcek Dam (Fig. 4) has an asphalt-concrete sealing skin. The grouting curtain extends down to 30–70 m in accordance with the quality of the neovolcanic subsoil (Chovan, 1997). The quality of the grouting on this dam was controlled by water pressure tests; however, about 40% of the results did not fulfil the criteria. Thus special attention was paid to both design and construction of the drainage and control system as well as careful reservoir filling. The observation boreholes (nos 10, 19, 30, ... 66 in Fig. 3) for the single borehole tracer method were built in the grouting curtain and the dam subsoil from the grouting gallery, in the dam body, and in the side slopes.

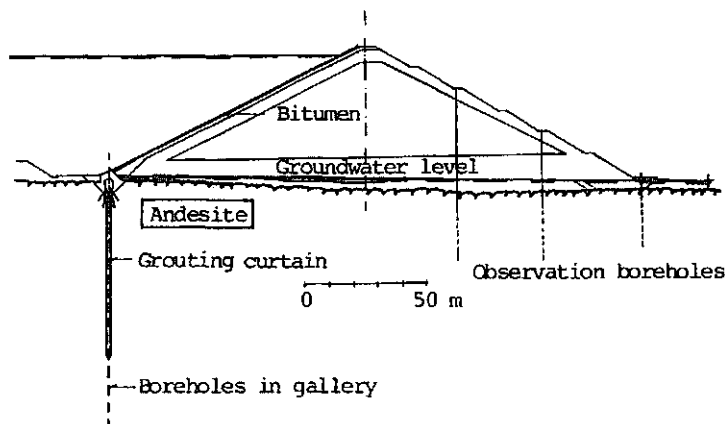


Fig. 4 Cross-section of the Turček dam.

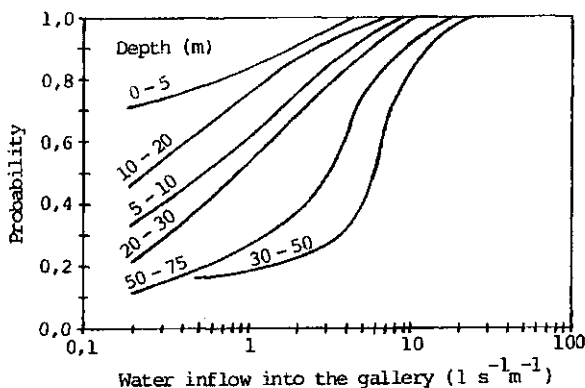


Fig. 5 Empirical distribution functions for affluent amounts into the gallery (Q) from various depths of grouting boreholes.

High quality data showing the great variability of the natural bedrock permeability at the grouting curtain were obtained through water pressure tests. At a pressure of 600 kPa, effluent amounts ranged between 0.1 and 100 $l min^{-1} m^{-1}$ with a median of 2.5 $l min^{-1} m^{-1}$.

Similar information was gained during the borehole works where amounts of water flowing from the boreholes into the grouting gallery were monitored. In the cases chosen the depth function of vertical discharge was also monitored by tracer methods. Having recalculated the amounts to the parts of the borehole with a height of 1 m and system arrangement for given depth increments empirical distribution functions for the valley part of the dam were obtained (Fig. 5). According to these results, layers less than 30 m below the grouting gallery were distinctly less permeable. Very high permeabilities were measured at depths from 30 to 50 m. Extreme overflows reached up to 20 $l s^{-1} m^{-1}$ within this layer.

Šivo & Richtáriková (1995) conducted radiocarbon analyses at this location. Water at a depth of 45 m was 1800 years old, but at a depth of 70 m only 800 years old. These results also show higher permeability and more active groundwater flow in deeper layers.

Another important fact is the mainly vertical direction of the fissures, approximately perpendicular to the dam axis. This required the curtain to be grouted mostly in sloping boreholes.

Complex geological and hydrogeological conditions, misguided advice on the grouting curtain depth and problems with grouting justify a thorough analysis of groundwater and seepage water flow by the finite element method at the beginning stages of construction.

Modelling was conducted, based on all the data and characteristics which were known in 1995. The permeability and anisotropy of the rock subsoil dominate other factors (such as grouting curtain depth) in controlling seepage volumes. Modelling results presented in a form of seepage amounts for a full reservoir and various alternatives (A, B, C, D) with corresponding entry data ranges are shown in Fig. 6.

An excellent drainage system enabling the identification of water seepage has been built under the dam. Measurement results after having reached the maximum water table in the reservoir in 1998 are shown in Fig. 6.

Having compared real and modelled seepage, it is observed that the best model used was the alternative A with the subsoil permeability coefficient $k_s = 3 \cdot 10^{-6} \text{ m s}^{-1}$ with anisotropy $\lambda = 1$ and grouting curtain permeability coefficient $k_c = 10^{-7} \text{ m s}^{-1}$ (this was validated by independent tracer measurements in the grouting curtain).

In Slovakia, these seepage volumes are significant, representing about 50% of the water which has to be drained into the riverbed under the dam.

CONCLUSIONS

Single borehole tracer tests were conducted during flooding and operation of the Liptovská Mara and Turček reservoirs. These enabled measurement of seepage amounts for comparison with the predicted values which had been estimated by the finite element method.

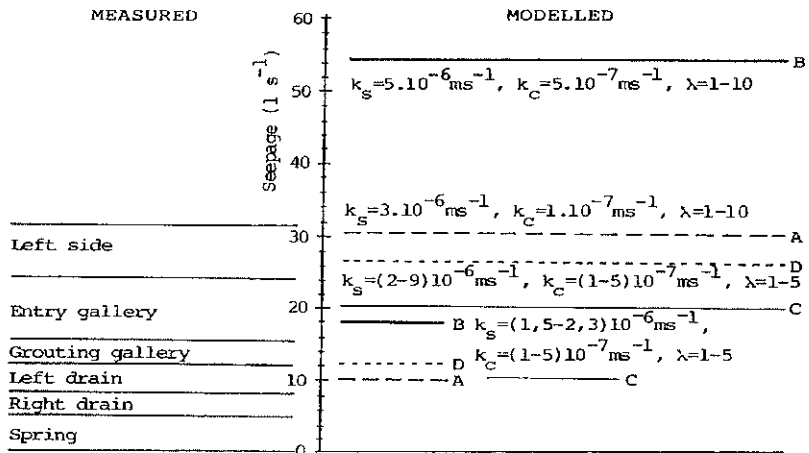


Fig. 6 Modelled and real seepage under the Turček dam: A to D—calculation alternatives, k_s —subsoil permeability coefficient, k_c —grouting curtain permeability coefficient.

Special attention focused on the stability problems of fine fills in rock fissures or gravel pores. Measured values of filtration velocities have never reached critical values for filtration stability.

During dam construction, grouting curtain quality was investigated by water pressure tests. The grouting curtains of both reservoirs sufficiently fulfilled their sealing function despite the fact that during construction the sealing criteria for water pressure tests were not fulfilled.

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