Analysis of Causes of Uplift Anomalies in the Čierny Váh Subsoil

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Abstract. The pumped storage hydropower plant of Čierny Váh was created by means of damming up the valley of the Čierny Váh River. The dam is 18.5 m high above terrain and 375 m long in the dam’s crest. Total capacity of the reservoir is 5.1 million m³. Complicated geological conditions in the subsoil of dam’s body – fractured dolomite with local occurrence of tectonic breccia and clays, with the occurrence of intense disturbances - called for the construction of the grouting curtain in the dam’s subsoil. Its depth is about 20 in the area of the riverine plain, and about 60 m in the areas of abutments. During foregoing operations of the structure, more than 30 years, local anomalies in the uplift development in the right abutment’s subsoil of the lower reservoir dam were recorded. Their abnormally high values on the downstream side of grouting curtain have become the subject of extensive discussion and a stimulus for its remediation. To ensure reliable operation of the hydraulic structure a comprehensive analysis of the impact of the long‐term operation of the reservoir on the dam safety was carried out. This included an examination of the causes of anomalous development of uplifts using FEM numerical modelling. The paper presents obtained results from this analysis.

1. Introduction

The dam was created in the years from 1976 to 1983 by means of damming up the valley of the Čierny Váh River by a dam whose height is 18.5 m above terrain and 49.2 m above foundation. Length of the dam in crest is 375 m. Total capacity of reservoir is 5.1 million m³, of which the volume 3.7 million m³ is used for pumping. The level fluctuates by 7.45 m between elevations 726.00 – 733.45 m. Geological composition of the subsoil of dam body is very heterogeneous (figure 1). In the left abutment, there are light grey fractured dolomites with local occurrence of tectonic breccia and clays placed, in the valley mostly tectonic breccia with the positions of slates, dark grey dolomite and dolomitic breccia, which continue also in the right abutment with the occurrence of intense failures. Due to mentioned complex geological conditions, a grouting curtain composed of bentonite-cement and chemical mixtures based on water glass was constructed to a depth of up to 60 m in the abutments and to a 15 - 20 m in the valley [4, 5].
Local anomalies in development of uplifts were during the foregoing operation of the water structure observed in the right side of dam’s subsoil (figure 2). These anomalies are situated in the subsoil of the operation building block (PB1), which is monitored with boreholes P47, P31a, P49 on downstream side of grouting curtain, P48, P32 on upstream side of grouting curtain and VZ12 inside the grouting curtain. Anomalous character of development of uplifts for the entire period of the operation can be illustrated by a pair of boreholes P48 – P47 (figure 3). Such locally abnormally high values on the downstream side of grouting curtain have become the subject of extensive discussion. To ensure a reliable operation of the hydraulic structure a comprehensive analysis of the impact of the long-term operation of the reservoir on the dam safety was carried out. This included an examination of the causes of anomalous development of uplifts using finite element method (FEM) numerical modelling.

**Figure 1.** Geological profile through grouting curtain: 1 – fluvial gravel sediments of Čierny Váh, 2 – light grey dolomite, 3 – dark grey dolomite, dolomitic breccia with the positions of slates, 4 – tectonic breccia with the positions of dolomitic breccia, 5 – dark grey breccia and flour, tectonic breccia of slates, 6 – dark grey dolomite, occasionally dolomitic breccia, 7 – plane of over thrust fault, 8 – fault plane [3]

**Figure 2.** Uplift in the subsoil of the lower reservoir dam – downstream side of grouting curtain
2. Analysis of causes of anomalous uplift development in the subsoil of dam by FEM

From a theoretical point of view, the task is a steady state, solved in the vertical plane. Mathematically, solving tasks of steady state filtration flow in a plane result from the continuity equation and Darcy's filtration law:

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial h}{\partial y} \right) = -q
\]

where: \( h \) is piezometric level (m), \( k_x, k_y \) - filtration coefficients in the direction of axis x, y (m. s\(^{-1}\)), \( q \) - inflow eventually outflow (m\(^3\).s\(^{-1}\)) of water.

The use of numerical methods without appropriate software program is not realistic. In our case, we applied the software GeoStudio [2], module SEEP/W, which allows solving FEM filtration flow tasks in the horizontal and vertical plane with free as well as pressurised water level. Uniqueness of the solution is ensured by boundary conditions on the border of the study area.

3. Calculation assumptions

Block PB1 situated on the right-hand part of the dam is located on the original riverbed of the Čierny Váh River. A specific feature of this area is local occurrence of permeable rock, with oblique outlet into the surface zone of the subsoil of block PB1 (figure 3). Losses of water by pressure tests in this area were 10 – 40 l/min/m/0.3 MPa. These corresponds to the permeability of rock environment 1.6 .10\(^{-6}\) - 6.5 .10\(^{-6}\) m. s\(^{-1}\) [6]. An important knowledge is a fact that locally permeable zone extends in the subsoil of right dam and partially in the block PB2 subsoil to a depth greater than the depth of the grouting curtain.

![Figure 3. Schematic layout of the permeability of geological environment in the subsoil of lower reservoir dam](image-url)

Numerical model scheme depicted in figure 4, is presented by measurement profile P48 - P47. Boundary conditions in the lower part were determined by water levels in reservoir (728.20 m a.s.l.) and in boreholes which monitors the level of water downstream the dam (713 - 714 m a.s.l.). During the engineering-geological and hydrological surveys were from the losses at the water pressure tests determined following permeability of subsoil (figure 4):

- overburden – thickness approx. 8 m, \( k = 2 .10^{-2} \) m.s\(^{-1}\) – 3.0 .10\(^{-4}\) m.s\(^{-1}\),
- quaternary – thickness approx. 11 m - \( k = 3.24 .10^{-8} \) m.s\(^{-1}\) – 3.24 .10\(^{-7}\) m.s\(^{-1}\),
locally permeable rock environment, ascending to the rock mass surface in the subsoil of block PB1 (the so-called lens), with thickness approx. 8 m - k = 1.62 \cdot 10^{-6} \text{ m.s}^{-1} – 6.54 \cdot 10^{-6} \text{ m.s}^{-1}.

dolomite, dolomitic breccia and flour - k = 3.24 \cdot 10^{-7} \text{ m.s}^{-1} – 8.4 \cdot 10^{-7} \text{ m.s}^{-1}.

Figure 4. Characteristic profile of a dam in the block PB1 and calculation assumptions

The backfill was assigned the value of the coefficient of filtration of local materials 
\( k = 3 \cdot 10^{-4} \text{ m.s}^{-1} – 10^{-6} \text{ m.s}^{-1} \) and the grouting curtain 
\( k = 1 \cdot 10^{-5} \text{ m.s}^{-1} \). Grouting curtain was modelled (in accordance with the realization) as double row, with fictional width of about 6 m and permeability 
\( k = 1.10^{-7} \text{ m.s}^{-1} \). Depth of downstream row of grouting curtain was assumed to be 20 m and the upstream row 13 m below foundation base. Causes of anomalous development of uplifts were analysed in form of parametric study [1]. For various combinations of permeability of rock environment and constant parameters of functional grouting curtain was searched such variant in which the uplifts were in accordance with the in-situ results. As a test criterion was selected information about the long-term development of uplifts in boreholes P47, P31a, P49, P48 and P32. It can be concluded that the measured values of uplift (piezometric levels in m a.s.l.) in the boreholes on the downstream side range from 725 m a.s.l. (P31a, P49) to 727 m a.s.l. (P47). In the boreholes situated on the upstream side of grouting curtain the average long-term values of uplifts range from 726.5 m a.s.l. in P48 to 727.5 m a.s.l. in P32.

4. Results of analysis

Based on the analysis of numerical modelling results, we have come to following knowledge that observed long-term anomalous evolution of the uplift in the P47 respectively P49, P31a was not confirmed in any real combination of the permeability of subsoil and grouting curtain. Due to this fact it was necessary to proceed to the hypothesis that the anomalies may be caused by failure of grouting curtain alone or existence of preferred seepage paths in the rock environment near foundation base (figure 5).

From a comprehensive analysis results, that every alternative of failures of grouting curtain or rock environment in the subsoil of block PB1 (near foundation base) is not in accordance with real measured values in situ. (Table 1, figure 6).

The obtained knowledge from the simulation of various real combinations of the permeability of the geological environment, as well as the failure phenomena in the subsoil of the PB1 block lead to the hypothesis about the occurrence of a specific spatial phenomenon. In the existing geological environment, a local inflow of water under grouting curtain in the right-sided dam with outlet under PB 1 can be assumed.
Figure 5. Layout of expected failures in the subsoil of block PB1; 1- degradation of grouting curtain near the foundation base – alternative 1; 2- degradation of rock environment near foundation base – alternative 2; 3- degradation of rock environment near foundation base in combination permeable lens and water level in reservoir through backfill – alternative 3

Table 1. Verification of the calculated uplift on the concrete seal foundation joint with measured values

| Alternative | Downstream face | Upstream face |
|-------------|----------------|--------------|
|             | Calculated (m a.s.l.) | Measured in situ (m a.s.l.) | Calculated (m a.s.l.) | Measured in situ (m a.s.l.) |
| Alt.1       | P47 720.80          | P47 727.0    | P49 725.0          | P31a 725.0          | P48 722.40          | P48 726.5          | P32 727.5          |
| Alt.2       | P47 719.06          | P47 727.0    | P49 725.0          | P31a 725.0          | P48 724.17          | P48 726.5          | P32 727.5          |
| Alt. 3      | P47 719.40          | P47 727.0    | P49 725.0          | P31a 725.0          | P48 727.00          | P48 726.5          | P32 727.5          |

The results of engineering-geological and hydrogeological survey here confirmed the presence of locally permeable rock in the area of foundation base of the block PB1 binding to similarly permeable rock environment at greater depths, below the lower end of the grouting curtain in the right-sided dam and block PB2 (figure 3). Given this fact and the results obtained from the previous solution of alternatives as well as the measured values of uplifts in measurement profile P48 - P47 and in specific profile P32 - VZ15 - P31, P31a, P49 the assumed hypothesis is realistic. This phenomenon was simulated through an influx of water into the locally permeable rock environment (the so-called lens), situated below the foundation base of the block PB1 (alt. 2). Inflow of water from the reservoir was simulated in different variants ranging from $5.4 \times 10^{-6}$ m$^3$.s$^{-1}$ to $9.0 \times 10^{-6}$ m$^3$.s$^{-1}$. The greatest consistency at the average water level in the reservoir 728.2 m. a. s. l. was obtained by simulated seepage amounts $5.76 \times 10^{-6}$ m$^3$.s$^{-1}$. Results of this solution in the form of vector of the filtration velocities and the course of piezometric heights are shown in figure 7. Under these assumptions on the upstream side of grouting curtain uplift value was calculated - 726.66 m a.s.l. (in P48 – measured 726.5 m a.s.l.) and on
the downstream side 727.02 m a.s.l. (in P47 measured 727 m a.s.l.). Compliance of the measured and calculated values of uplifts confirmed the reality of the assumed hypotheses.

**Figure 6.** Calculated uplifts acting at the foundation base of block PB1 at an average (728.20 m a.s.l.) with the assumption of failure near the foundation base

**Table 2.** Calculated uplifts on foundation base of concrete object

| Coordinate | Uplift at w. level | Uplift at w. level |
|------------|--------------------|--------------------|
|            | 728.20 m.a.s.l.    | 733.20 m.a.s.l.    |
| 100.00     | 718.75             | 720.16             |
| 102.32     | 722.56             | 724.95             |
| 104.64     | 724.68             | 727.61             |
| 106.96     | 726.66             | 730.08             |
| 108.84     | 726.73             | 730.18             |
| 110.72     | 726.82             | 730.29             |
| 112.59     | 726.90             | 730.39             |
| 114.47     | 726.96             | 730.47             |
| 116.35     | 727.02             | 730.54             |

Downstream side

| Coordinate | Uplift at w. level | Uplift at w. level |
|------------|--------------------|--------------------|
|            | 728.20 m.a.s.l.    | 733.20 m.a.s.l.    |
| 118.90     | 719.05             | 721.48             |
| 120.09     | 722.65             | 725.06             |
| 121.28     | 724.70             | 727.10             |
| 122.36     | 726.74             | 729.10             |
| 123.43     | 728.69             | 730.69             |
| 124.57     | 726.93             | 730.93             |
| 125.69     | 727.09             | 731.09             |
| 126.81     | 727.26             | 731.26             |
| 127.93     | 727.47             | 731.47             |

Upstream side

| Coordinate | Uplift at w. level | Uplift at w. level |
|------------|--------------------|--------------------|
|            | 728.20 m.a.s.l.    | 733.20 m.a.s.l.    |
| 110.72     | 726.82             | 730.29             |
| 112.59     | 726.90             | 730.39             |
| 114.47     | 726.96             | 730.47             |
| 116.35     | 727.02             | 730.54             |
| 118.90     | 728.05             | 730.55             |
| 120.09     | 728.65             | 730.65             |
| 121.28     | 729.05             | 730.75             |
| 122.36     | 730.05             | 730.85             |
| 123.43     | 730.69             | 730.95             |
| 124.57     | 731.09             | 731.29             |
| 125.69     | 731.49             | 731.69             |
| 126.81     | 731.89             | 732.09             |
| 127.93     | 732.29             | 732.49             |
| 129.43     | 732.68             | 732.88             |
| 130.42     | 732.88             | 733.08             |
Presented FEM analysis of filtration flow in the subsoil of critical measurement profile P48-P47 and P32 – Vz15 – P31, P31a, P49 confirmed the hypothesis that the water flows under grouting curtain in the section E2 with consequent ending of seepages through oblique permeable zone of the rock environment to the closed region on the downstream side of grouting curtain with the limited possibility of its outflow. At the same time, the analysis disproved the hypothesis that the cause of high uplifts in measurement profiles P48-P47 and P32 – Vz15 – P31, P31a, P49 is degradation of grouting curtain in the vicinity of the foundation base.

Figure 7. Calculated uplifts acting at foundation base of block PB1 at an average (728.2 m a.s.l.) and maximal (733.2 m a.s.l.) water level in reservoir

5. Conclusions
Anomalies in the development of parameters of filtration flow are not rare in the dams of hydraulic structures. This results from the wide variability of the geological environment, which may in certain circumstances cause a non-standard development of seepage flow mode (water levels, uplift, filtration velocities, etc.). Due to the interaction of dams with heterogeneous natural environment it is important to clarify the causes of such anomalous events. Only then it can be reasonably evaluated whether such events are in terms of dam safety risky or not. Where necessary, remediation measures can then be reasonably optimised. In the paper, the experiences gained from the analysis of the causes of
anomalous development of uplifts in the subsoil of the lower reservoir dam of pumped storage hydropower plant (PSHPP) Čierny Váh were illustrated. Based on the large database of measured parameters of filtration flow, together with the realization of special measurements of filtration velocities and using the appropriate software, the reasons of the local anomalies in uplifts could be clarified. Their understanding is for the operator an indispensable part of ensuring safety and reliable operation of the water structure in the future.

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