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GEOPHYSICAL, NUMERICAL AND STATISTICAL METHODS AS PART OF REVIEWING DAM SAFETY

GEOFIZIKALNE, NUMERIČNE IN STATISTIČNE METODE KOT DEL OCENE VARNOSTI PREGRAD

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Abstract

The first dams were built in Slovakia more than 500 years ago. Basic features of these historic hydraulic structures can also be seen in structures built later in the 20th century. Most dams were built from local materials. These are mostly heterogeneous earth-fill or rock-fill dams (Bednárová et. al., 2010). The determining factors of such choices are engineering-geological and geotechnical conditions of the natural environment. In their design, construction, operation and safety control the reliability of input data is crucial. The wide variability of geological conditions and methods for determining the properties of soils and rock materials plays a very important role. Besides common methodological approaches for solving these issues, complementary methods (geophysical, numerical and statistical) may also be applied. This article describes some case studies of applying such methods in Slovakia.

Keywords: dam, geology, interaction, grouting curtain, efficiency, geophysics, numerical methods.

Izvleček

Prve pregrade na Slovaškem so bile zgrajene pred več kot 500 leti. Osnovne značilnosti pri oblikovanju teh zgodovinskih pregrad so vidne tudi na objektih, zgrajenih kasneje v 20. stoletju. Večina pregrad je zgrajenih iz lokalnih materialov. Prevladujejo predvsem heterogene zemeljske in skalometne pregrade (Bednárová et. al., 2010). Pri izbiri tipa pregrade so prevladujoči predvsem inženirsko-geološki in geotehnični pogoji na lokaciji objekta. Za zasnovo, izvedbo, obratovanje in kontrolo varnosti pregrad je odločilna zanesljivost vhodnih podatkov. Ključno vlogo imajo pri tem spremenljivost geološkega okolja in metode za določanje lastnosti zemljin in hribin. Poleg običajnih metodoloških pristopov lahko k reševanju problematike vhodnih podatkov pripomore tudi uporaba komplementarnih metod, kot: geofizikalne, numerične in statistične metode. V članku so prikazani primeri uporabe teh metod na Slovaškem.

Ključne besede: pregrada, geologija, interakcija, injekcijska zavesa, učinkovitost, geofizika, numerične metode.

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1. Introduction

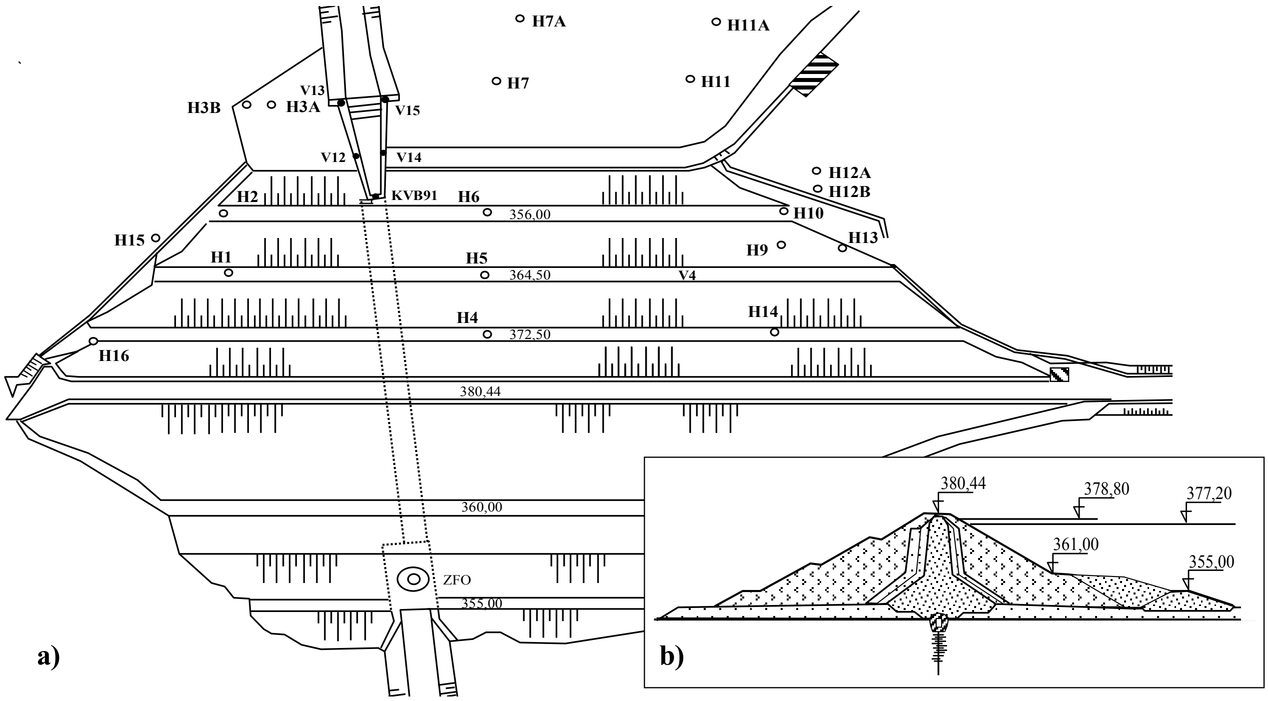
The issue of assessing safety of dams made of local materials is an important part of reliable operation of reservoirs. The assessment is based on monitoring the behaviour of dams during operation. The values measured in situ are compared to the assumptions of the project, the limit values and eventually the critical values. In some cases, the measured values indicate anomalous development. In order to clarify these effects it is appropriate to use complementary methods of inspection - geophysical, numerical and statistical. The application of these methods in Slovakia has a long tradition. In particular, geophysical methods of measuring filtration velocities in wells discovered a potential risk of failures in filtration stability in several cases. On the other hand application of numerical and statistical methods in connection with a large database of measured values in situ represents a rational approach for a comprehensive assessment of dam safety especially in terms of the impacts of long-term operation.

2. Geophysical methods as a part of reviewing dam safety

An important part of assessing dam safety is filtration stability. Using routine monitoring – measurement of water levels, uplifts and seepages, without knowing the intensity of filtration flow, filtration stability cannot be reliably assessed. Geophysical measurements of filtration velocities in wells provides appropriate information for this purpose – an overview of the distribution of the intensity of groundwater flow and seepage water in wells, depending on depth. Systematic measurements of filtration velocities provide knowledge about the trend of their development, both average and maximum values. From these, the temporal and spatial intensity distribution of the filtration flow can be deduced in the study area, and areas where there is a risk of internal suffusion can be identified. In Slovakia, special geophysical measurements of filtration velocities in wells have been in use for more than 40 years. During this long period their usefulness was confirmed, as shown by the dam Klenovec. Dam Klenovec was built in years 1968 – 1974 on the river Klenovecká Rimava and has a reservoir of 8.43 10^6 m^3 (Bednárová et. al., 2010). The dam is rock-earth with centred silt sealing, widened in lower part (Fig. 1). Geophysical measurements of filtration velocities have been performed from the year 1971, from the construction stage. First results, measured after impounding the reservoir recorded no anomalies. After almost 10 years of operation (in 1983) the recorded filtration velocities in wells in the left abutment exceeded critical values, so conditions for failure of filtration stability were met. After their repeatable occurrence in following years (1984 to 1988) it was decided to implement treatment with the aim of interrupting the expected preferred seepage paths in the subsoil of the dam. The grouting curtain was retightened on the location of the left abutment. Subsequent geophysical measurements of filtration velocities (but also uplifts in the subsoil of dam) performed 1992–2007 confirmed the positive effect of the treatment. Intensity of underground and seeping water flow in the left abutment decreased markedly, which is confirmed by the measurement results illustrated in Fig. 2. At present the development of the parameters of filtration flow on Klenovec dam is consolidated and does not show any symptoms indicating the failure of filtration stability.

3. Numerical methods as a part of reviewing dam safety

Not many engineering structures are as dependent on natural conditions as dams. There is a wide range of aspects affecting their design. The same assumption is valid for grouting curtains in their subsoil. Optimization of their parameters depends on the environment where they are located, mainly permeability of dam subsoil, but also materials inbuilt into the body of dam, type of drainage system etc. The results of parametric studies carried out using finite element method (FEM) confirm it as well (Lukáč and Bednárová, 2006).



a) Situation (H – piezometers) b) Cross section of dam
a) Situacija (H – piezometri) b) Prerez pregrade

Figure 1: *Klenovec dam.*

Slika 1: *Pregrada Klenovec.*

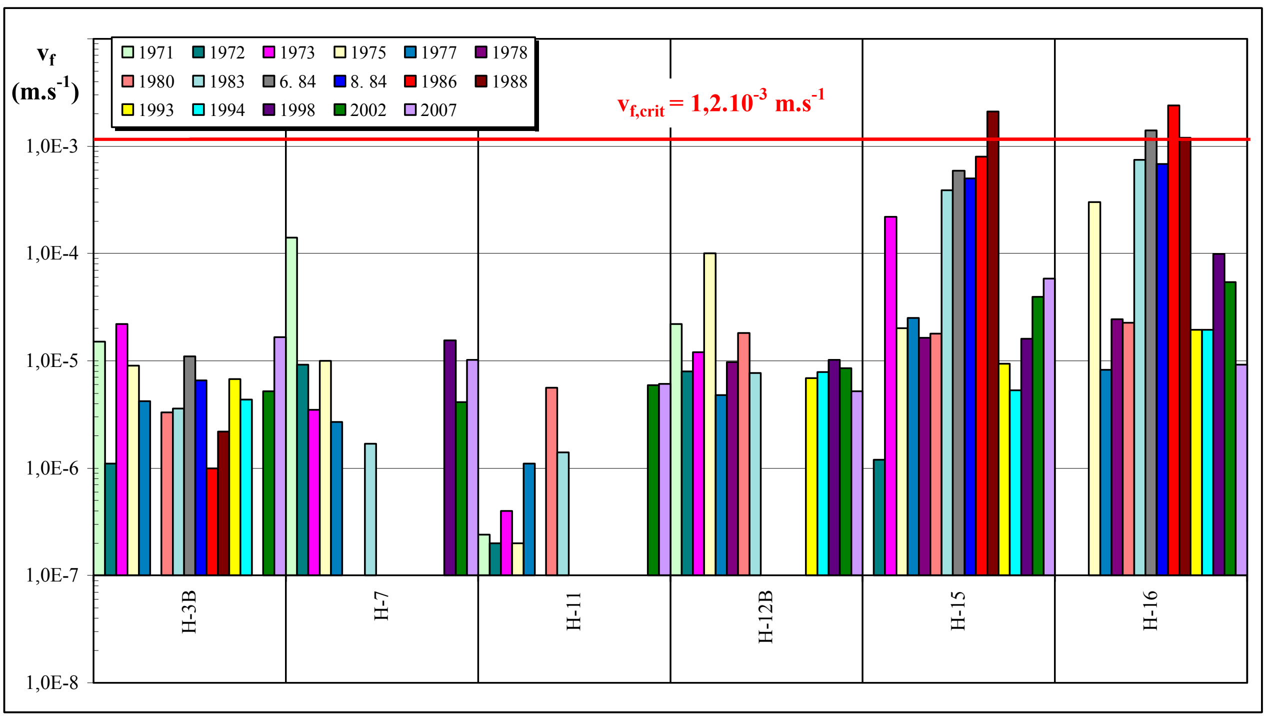


Figure 2: *Development of maximal filtration velocities in rock subsoil of Klenovec dam.*

Slika 2: *Razvoj največjih filtracijskih hitrosti v hribinski podlagi pregrade Klenovec.*

These aspects were analysed in detail for various types of dams and several geological conditions (Fig. 3).

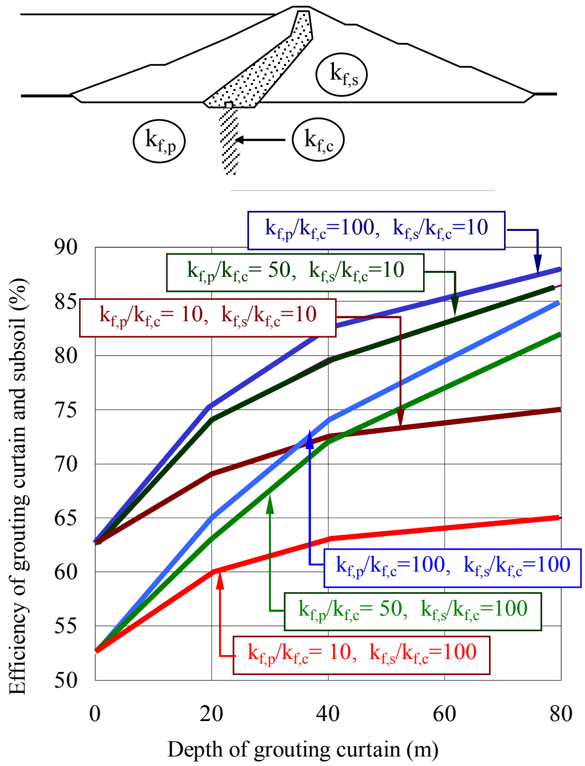


Figure 3: *Effect of depth of grouting curtain and permeability of the environment on its efficiency*

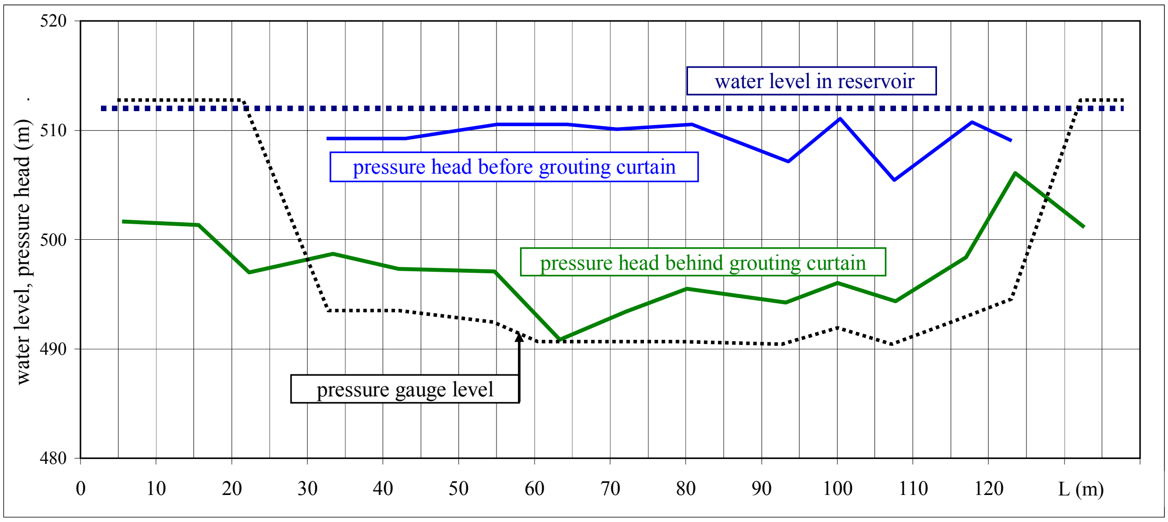
Slika 3: *Vpliv globine injekcijske zavese in prepustnosti hribine na njeno učinkovitost.*

According to the results, in a relatively homogeneous geological environment, prevailing factors affecting grouting curtain efficiency are its parameters – mainly depth. In a heterogeneous environment, permeability of dam subsoil plays an important role. The fact that the effect of these parameters can be significant is confirmed by in-situ experiences (Bednárová, 2006). To illustrate the issue we present the knowledge gained through measurements on Vlčia dolina and Nosice dams. Both are concrete gravity dams equipped with grouting curtains of relatively constant width, depth and permeability. Both dams are equally old, built in the 1950s. They serve the same purpose – hydropower. Despite that, different results were recorded in their grouting curtain efficiency (Bednárová and Minárik, 2007). In case of Vlčia dolina dam the efficiency is high and long-term stable (Fig. 4a). The dam subsoil is relatively homogeneous, created by diorites.

In Nosice dam the efficiency of the grouting curtain is highly variable (Fig. 4b). In some profiles a value of 80 % is reached and in others only approximately 30 %. This is caused by a strong heterogeneity of the rock mass and different shape of the foundation base. The dam is situated in a geological location of Carpathian flysch, which is characterized by alternation of sandstones, claystones and agglomerates.

This analysis was performed on several Slovak dams. Obtained results confirmed the significant effect of geological environment on the efficiency of grouting curtains. The know-how was then effectively used to design a grouting curtain in the subsoil of Turček dam. It is a rock-fill dam with asphalt-concrete upstream face sealing. The height of the dam is 60 m. The dam creates a reservoir with a total volume of 9.9 10^6 m^3 which serves for drinking water supply. The hydraulic structure was put into operation in 1996. It is the first dam in Slovakia located in the bedrock of volcanic origin, in Kremnica Mountains. The subsoil is composed of strongly tectonically disrupted andesites, liparites and tuffs. The results of Lugeon tests confirmed that the subsoil of the dam is extremely heterogeneous and locally highly permeable. According to the original studies, the grouting curtain should be approximately 100 m deep.

To optimise the grouting curtain parameters, an extensive parametric FEM study was performed. This study results from lessons learned and experiences acquired through FEM numerical modelling applied on other hydraulic structures in Slovakia. Grouting curtain parameters were scoped in several geological profiles, allocating relatively homogeneous sections of dam subsoil. It was established that the final design of the grouting curtain depth under the Turček dam should be between 35 m and 60 m to meet the efficiency requirements. With such variable depth of the grouting curtain, stemming from the disturbance of geological environment, relatively stable efficiency was reached (Fig. 5), confirmed by more than 10-year long operation of the reservoir.



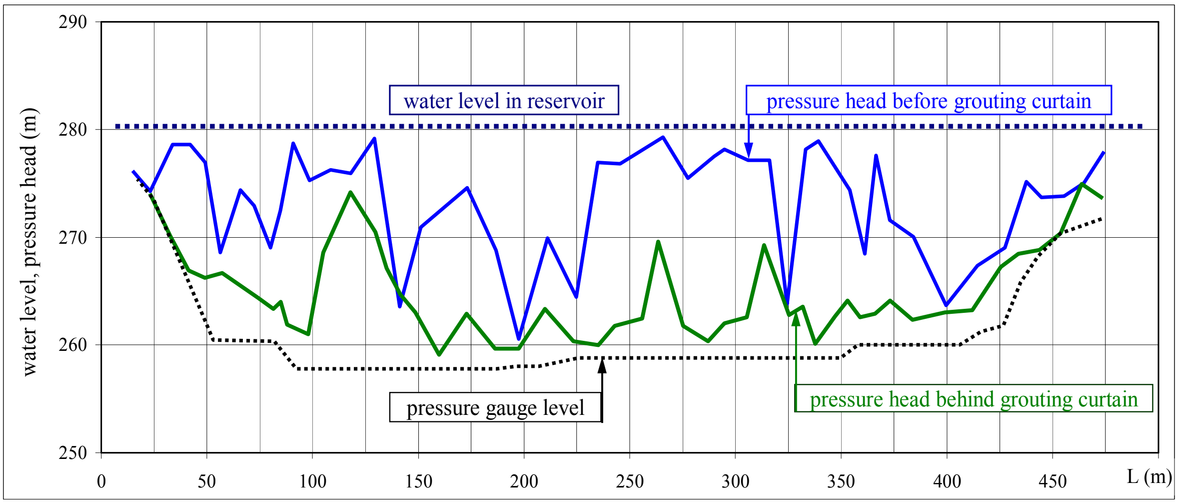


Figure 4: *Pressure heads in the subsoil of dam Vlčia dolina (top) and Nosice (bottom).*

Slika 4: *Tlaki v zemljinski podlagi pregrade Vlčia dolina (zgoraj) in Nosice (spodaj).*

The presented results of grouting curtain optimisation in the design stage require vast knowledge on geological composition of the area. Numerical methods and authentic input data can significantly contribute to effective design of seepage remedies.

4. Statistical methods as a part of reviewing dam safety

When analysing the development of the water level regime, the interconnection between water levels in monitoring objects and water levels in reservoir can be traced from numerical and graphical processing of the results of in-situ measurements. Also, it can be partially confirmed or refuted by a simple test – calculating the correlation coefficients of monitored parameters, namely groundwater and seepage water levels and water level in the reservoir. It is a simplified form of examination of the existence of mutual interconnection between the monitored phenomena. Correlation between these phenomena is proof of the functionality of monitoring and also supplements the information about the nature of development in the filtration flow in the body and subsoil of the dam.

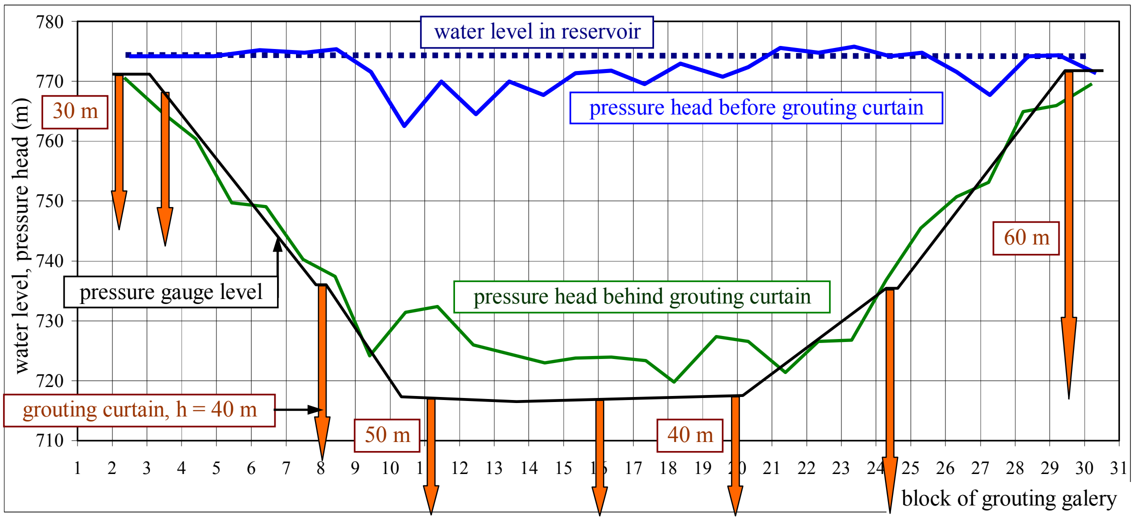
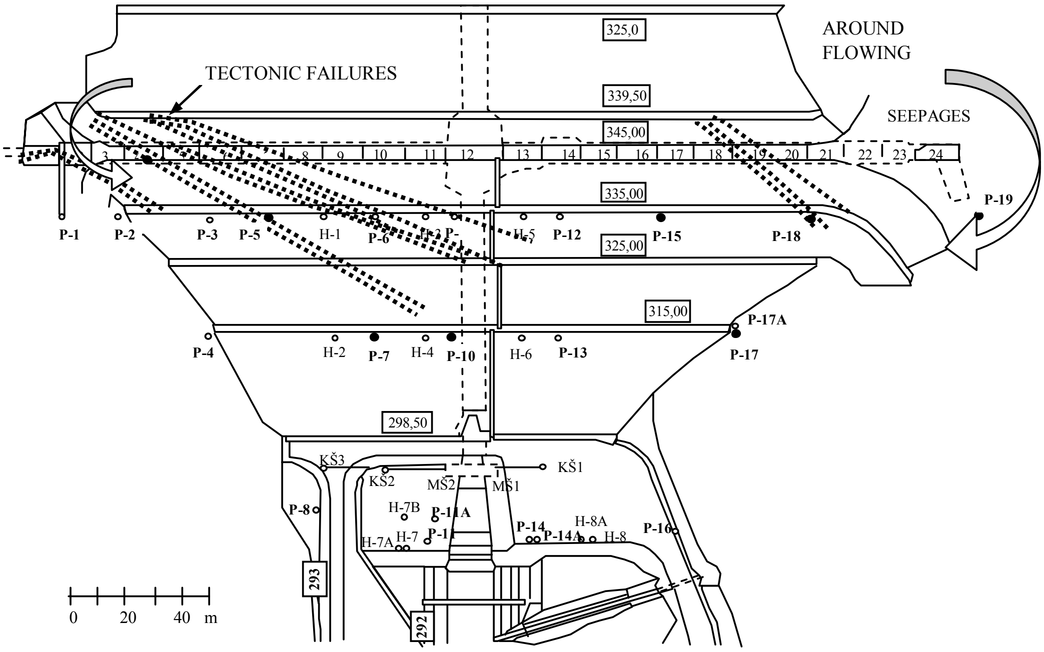


Figure 5: *Pressure heads in the subsoil of dam Turček*

Slika 5: *Tlaki v zemljinski podlagi pregrade Turček*



P-1 to P-19 observation wells for rock subsoil H-1 to H-8 observation wells for gravel subsoil
MŠ1, MŠ2 shafts for measurement of seepages 1 to 24 blocks of grouting gallery

Figure 6: *Situation of dam Starina*

Slika 6: *Situacija pregrade Starina*

To illustrate this, we present the results obtained on the dam Starina. It is an earth-fill heterogeneous dam with internal silt sealing. It is located on the River Cirocha, in the north-eastern region of Slovakia. With the height of 50 m it creates an accumulation volume of 59.9 10^6 m^3. It is the largest drinking water supply reservoir in Slovakia. Construction of the Starina dam was completed in 1987. Morphology of the territory predestines seepages to the left abutment of the dam (Fig. 6).The left-sided bay of the reservoirs in the immediate vicinity of the dam profile and geological composition of the environment create conditions suitable for the existence of this phenomenon (Bednárová et al., 2006).

The development of filtration flow in the dam foundation is also significantly affected by occurrence of failure zones (tectonic faults).

Existence of seepages in the abutments can be confirmed or refuted by in-situ measurements of water levels, uplifts and sometimes also seepages. From the measured values and in particular the trend of their development in continuity with the water level in the reservoir, both functionality of the seepage measures and the functionality of the observation system can be deduced. However, there are also cases where the process of the seepage regime development cannot be clearly defined. The causes may be various: sensing parts of piezometers are installed shallow under the foundation base of gallery and downstream piezometers show no values, drainage system in the abutments is not equipped so that it can distinguish seepage from the water flowing from slopes, water level mode can be continuously connected with the level in the reservoir, but can be marked by other factors etc.

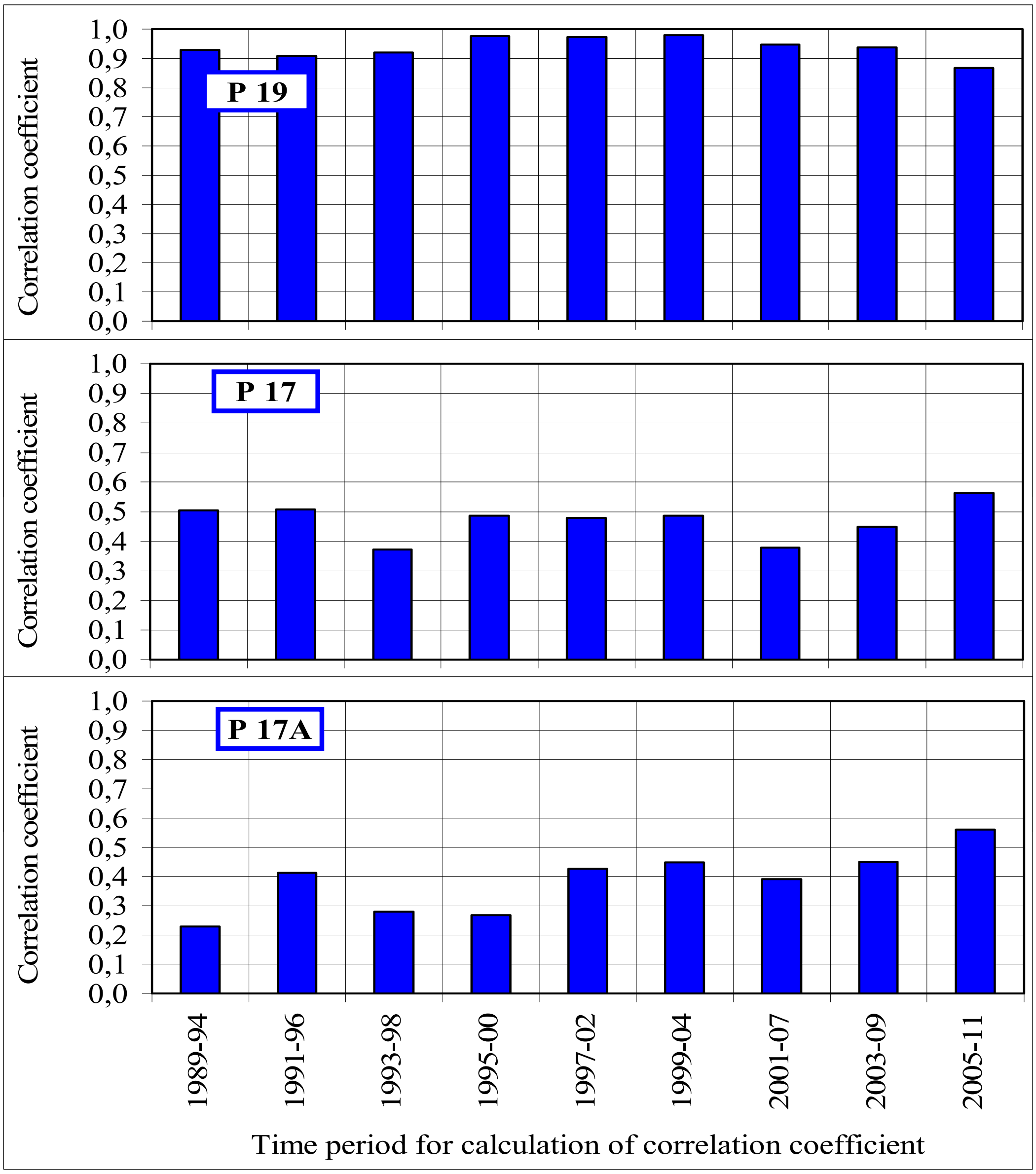


Figure 7: *Trend of the development of correlation coefficients – left side of the dam*

Slika 7: *Trend razvoja korelacijskih koeficientov – leva stran pregrade.*

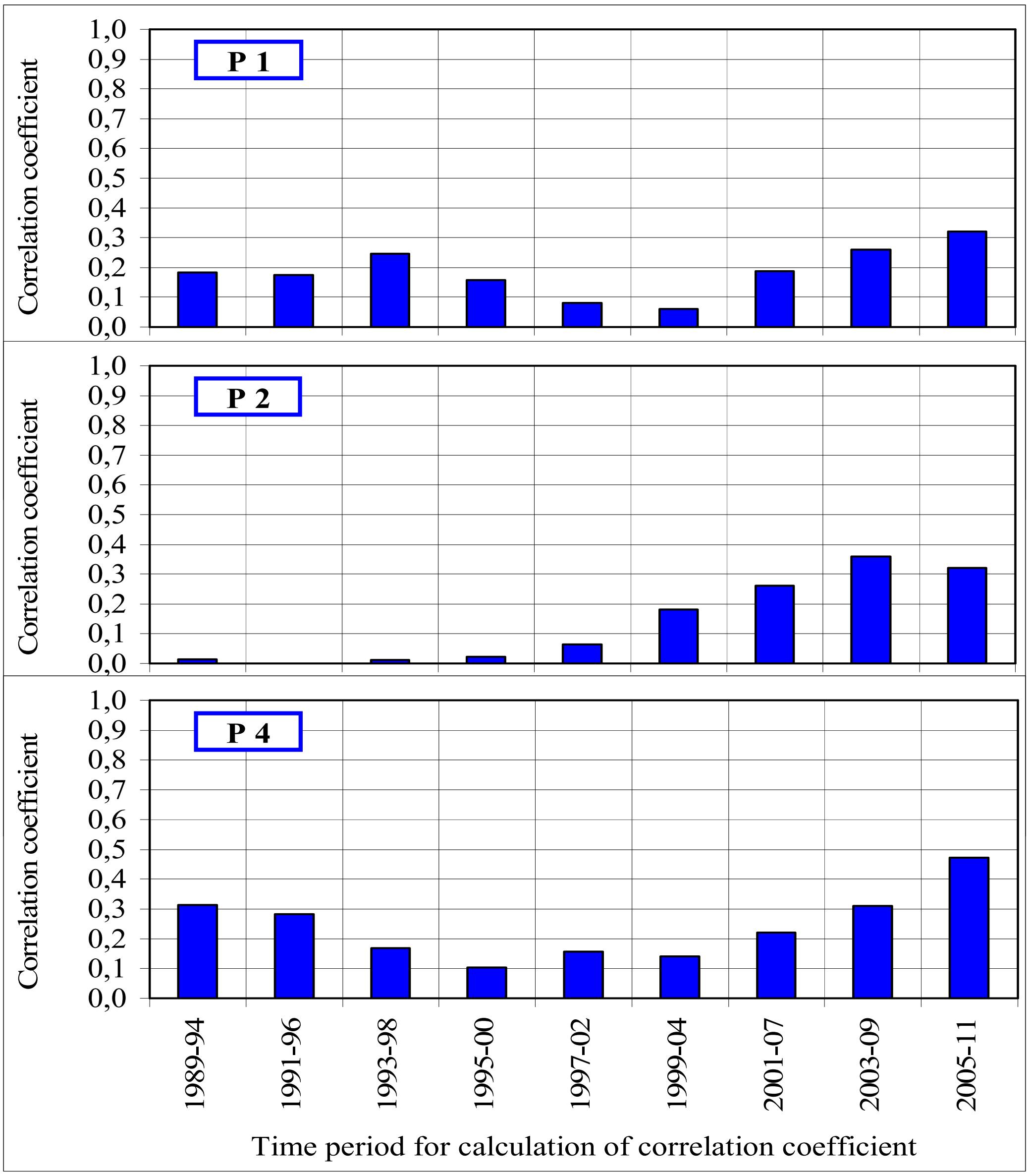


Figure 8: *Trend of the development of correlation coefficients – right side of the dam*

Slika 8: *Trend razvoja korelacijskih koeficientov – desna stran pregrade.*

Therefore, in assessing the reliability of seepage measures anything that can contribute to the clarification of such a complex process as seepages in abutment is appropriate. For large datasets of in-situ measurements a statistical approach can be used as a complementary method of analysing the process of seepages in abutments, or even the existence of preferred seepage paths. These effects can be specified by means of analysing the correlation coefficients between water levels in wells and the water level in the reservoir. Principle of this methodological approach is in the analysis of the correlations between the studied variables at several time intervals. It is assumed that if mutual continuity between the parameters clearly exists, the correlation coefficient should be proven at different intervals, regardless of load states. Similar results can be expected in cases where there is no correlation between the monitored phenomena. For Starina dam such an analysis was performed for the period 1987 - 2012, on 6-year datasets of measurements (Bednárová et al., 2009). The results showed that the correlation coefficients in the observation objects situated in abutment areas of dam are variable. Significant interconnection with the water level in the reservoir is recorded in wells on the left side of the dam (P19, P17, P17A – Fig. 7).

In contrast, in the monitoring objects P1, P2 and P4 (Fig. 8), which are inbuilt in the right slope of the valley the calculated correlation coefficients are insignificant. In other monitoring objects correlation coefficients achieve variable values. From the results it can thus be concluded that while in the left-hand abutment the presence of seepages is undisputed (P19, P17 and P17A), in the right abutment (P1, P2 and P4) it is improbable. The presented method of processing the measured water levels in its simplicity may help to clarify the hidden links that cannot always by detect from graphical processing of in-situ measurements.

Also noteworthy is the trend of development of correlation coefficients for the analysed period of the operation of hydraulic structure Starina. Obtained results can also indicate if the process of filtration flow of groundwater and seepage water is consolidated. From an increasing trend in the correlation coefficients it can be deduced that the risk of developing preferred seepage paths is increasing, while their decrease may indicate influence of other factors of the natural environment, or clogging of the preferred seepage paths. In any case, it is appropriate to closely monitor further development and in context with the results of in-situ measurements - the development of water levels, uplifts and seepage velocities in the affected area, assess which of the considered hypotheses is realistic.

5. Conclusion

Monitoring of dams is an important part of inspecting their safety and reliability during operation. However, even where automatic recording of all measured values is provided it cannot be clearly stated that control is perfect. Therefore, it is important to use all opportunities that can help improve the safety and reliability of these important structures. Presented special measurements of filtration velocities, the use of numerical methods in the design of dams, or in clarifying anomalies using inverse models, as well as apparently simple statistical approaches to the processing of in-situ measurements are such possibilities. Experience from dam operation in Slovakia shows that using such methods for assessing the safety of hydraulic structures is reasonable and efficient in assuring safe operation of hydraulic structures. They have an important position in the set of measurements and observations.

Acknowledgements

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