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POSSIBLE APPROACHES OF NUMERICAL MODELLING OF SEEPAGE ANOMALIES AND CUT-OFF WALL SOLUTIONS FOR EARTHFILL DAMS

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Abstract

Seepage is a frequent cause of dam safety problems and often leads to internal erosion or suffusion. A case study of a small earthfill dam in Slovakia, i.e., the Lozorno Dam, has exhibited anomalies in the development of seepage since its commissioning. This has been manifested by increased water levels in its observation boreholes and the occurrence of fine sand deposits in its relief wells. The objective of this study was to analyze the causes of these anomalies and propose effective remedial measures. The field monitoring data, including the groundwater levels and seepage flows, were evaluated and complemented by numerical modeling. The models were calibrated against long-term measurements in key observation profiles and subsequently applied to assess different remediation scenarios. The results demonstrated that local permeable sandy soils on the left valley slope are the primary source of the anomalous seepage. Parametric studies showed that the construction of a cut-off wall (COW) significantly reduces groundwater levels, seepage, and hydraulic gradients below critical limits. The findings provide practical recommendations for the remediation of earthfill dams in similar geological settings and highlight the importance of integrating monitoring and modeling in dam safety management.

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Key words

- Seepage,
- Anomalies,
- Internal erosion,
- Numerical model.

1 INTRODUCTION

The safety of earthfill dams remains a key issue in water management, as seepage and internal erosion are among the most frequent causes of dam incidents and failures (Lukáč and Bednárová, 2006). Similar issues have been reported in numerous small reservoirs across Central Europe, where geological heterogeneity and aging structures complicate seepage control and maintenance (El-Molla and Kilit, 2025). Excessive or uncontrolled seepage may reduce the stability of a dam body, initiate suffusion processes, and ultimately compromise its structural integrity (Fell et al., 2003). The problem is especially relevant for small and medium-sized reservoirs, where geotechnical conditions are often complex and the safety margins are lower compared to large dams (Foster et al., 2000; Bulletin 99, 1995; Bulletin 111, 1998).

International experience has shown that dam safety cannot rely solely on initial design assumptions. Continuous monitoring and the systematic assessment of seepage processes are indispensable (Kotaška and Říha, 2023). Numerous case studies have documented that anomalies in the development of groundwater levels or seepage discharges frequently precede the onset of internal erosion. The early identification of such anomalies is therefore crucial for the prevention of failures (Říha, 2013).

In Slovakia, several small earthfill dams have required rehabilitation due to seepage-related problems. The Lozorno Dam, which is located in the Morava River basin, represents a notable example (Bednarová et al., 2023). Since the dam's commissioning in 1986, repeated anomalies have been observed, including elevated water levels in observation boreholes and the washing out of fine sand particles into relief wells. These manifestations indicated insufficient filtration stability in certain zones of the foundation and raised concerns regarding the long-term reliability of the structure. Previous technical assessments suggested that local geological heterogeneities, particularly the presence of semi-permeable to permeable sandy layers in the valley slopes, may be responsible for the anomalous seepage regime. However, the available analyses did not provide a comprehensive explanation of the causes or a reliable basis for designing corrective measures. A systematic approach combining the detailed evaluation of monitoring data with numerical modeling was therefore required (Fadaei-Kermani, et al., 2019; Kheiri, et al., 2020).

The aim of this study is to analyze the causes of the development of the anomalous seepage from the dam and to propose technically feasible remedial measures. Specifically, the study focuses on assessing the long-term monitoring data of the groundwater levels and seepage flows, verifying and applying numerical models of the groundwater flow through the dam body and subsoil, and evaluating the effectiveness of a cut-off wall as a remediation measure (Beiranvand and Komasi, 2021). By integrating the monitoring and modelling of the dam, the study seeks to contribute to a better understanding of seepage anomalies in small earthfill dams and provide guidance for similar cases under comparable geological and operational conditions. The approach also illustrates the practical applicability of coupled monitoring–modeling workflows in dam safety management.

2 SITE OF THE CASE STUDY

The Lozorno Dam is situated in the western part of Slovakia, in the Morava River basin, southeast of the town of Lozorno (Fig. 1). The earthfill dam was constructed to provide irrigation water, flood protection, and environmental flow support for the Suchý stream. Additional benefits include fish farming and recreational use. The total reservoir storage capacity is $2.05 \cdot 10^6$ m³.

Fig. 1 *Visualization of the geographical location of the Lozorno Dam*

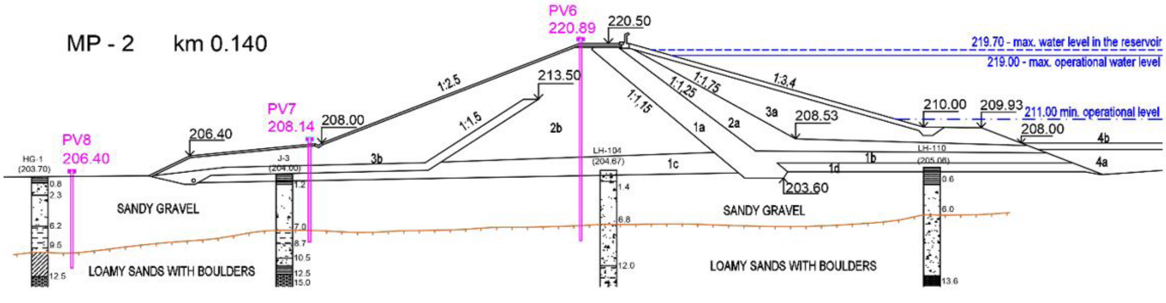

Fig. 2 *Cross-section of MP-2 profile at km 0.140*
1a – inclined sealing core (clayey silts), 1b – upstream sealing blanket (clayey silts), 1c – sealing blanket (silty-sandy clays), 1d – sealing blanket on the upstream side, 2a – upstream stabilizing prism (silty sands), 2b – downstream stabilizing prism (silty sands), 3a – upstream stabilizing prism (sandy-clayey gravels), 3b – inclined and horizontal drain (sandy gravels), 4a – extended sealing blanket in the reservoir (clayey silts), 4b – cover of the sealing blanket

The dam has a maximum height of 16 m above the foundation joint and 12.5 m above the terrain, a crest length of 426 m, and a crest width of 5 m. The upstream slope is 1:3.4 to 1:2.5, while the downstream slope ranges from 1:2.5 to 1:10 (Fig. 2).

The structure incorporates an inclined clay sealing supported by a sealing carpet, which is unusual for dams of this type. The dam body predominantly consists of clayey-sandy soils (loamy sands) with 20–25% silt and approximately 10% clay particles, which are generally considered suitable for homogeneous earthfill dams. Due to the composition of the materials built into the dam body, i.e., without stabilizing prisms made of permeable materials, the dam can be typologically classified as a zoned dam.

2.1 Geological conditions of the dam subsoil

The foundation consists of Quaternary gravelly-sandy sediments with irregular interlayers of sandy loams and loamy sands. These deposits reach depths of 4.5 to 10.5 m. Deluvial sediments predominate on the valley slopes; they comprise sandy to loamy-sandy soils with approximately 15% clay particles and up to 40% coarse gravel and rock fragments. In the alluvial plain, sandy clays, gravelly clays, and clayey sands were identified; they are underlain by loamy and clayey gravels with boulders of 10–30 cm in size. The Neogene is represented by sandy clays and loamy sands with gravel fragments and small boulders up to 6 cm.

Hydraulic conductivity tests identified two principal groups of material:

- semi-permeable to permeable sands with fine-grained admixtures (in the PV2, PV3, PV4, and PV5 boreholes), especially on the left valley slope and locally, i.e., gravels with admixtures of fine-grained soils (PV14) on the right valley slope (Fig. 4),
- low-permeable to quasi-impermeable (gravels with loamy or clayey particles) predominantly found on the alluvial plain, and in most parts of the dam body.

2.2 Monitoring system

The dam is equipped with a monitoring system designed to observe deformations, groundwater levels, seepage discharges, and filtration rates. The system comprises observation boreholes installed in the dam body and foundation, as well as relief wells and gauging shafts, which collect seepage water from inclined and horizontal drains connected to a longitudinal collector pipe. Seepage from sections of approximately 15 m is diverted through pipes into individual shafts, which are further interconnected by a collecting pipe leading to a main collection shaft (Fig. 4). A sealing carpet was also constructed to reduce seepage through the dam foundation. All the observation boreholes showed a very strong correlation with the reservoir water level, with the correlation coefficients exceeding 0.9, except for borehole PV8, where the lowest value of 0.63 was calculated. During the reservoir's operation at the maximum water level, observation boreholes PV7 and PV8 repeatedly recorded water levels exceeding the limit values. In addition, deposits of fine sand washed out from the dam subsoil were detected in relief wells in the left-hand part of the foundation. These findings indicated active suffusion processes and insufficient filtration stability.

A detailed inspection suggested that the open bottoms of several shafts, together with defects in the collecting pipe, were the likely cause of the observed suffusion phenomena. To address these issues, the drainage system in the left downstream slope was reconstructed in 2019. The reconstruction included the replacement and leveling of the collecting pipe, as well as concreting the bottoms of shafts MS13 to MS21. These measures eliminated the transport of fine particles into the shafts and reduced the seepage collected in the left-hand part of the dam foundation (Fig. 4). Nevertheless, groundwater levels in boreholes PV7 and PV8 remained above the specified limits, i.e., the threshold values (Fig. 5). This situation provided the rationale for conducting a detailed study to clarify the causes of the development of the anomalous seepage and to propose remedial measures.

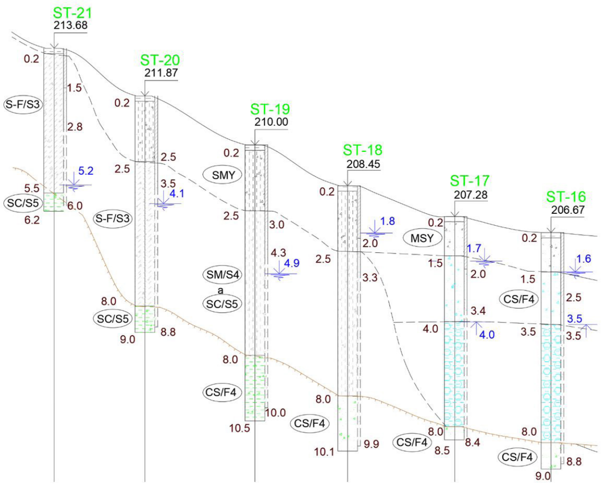

Fig. 3 Detail of geological composition on the right-hand side of the dam

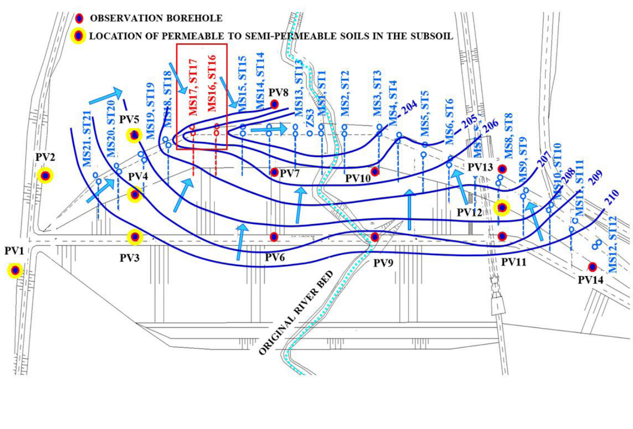

Fig. 4 Position of observation boreholes and an overview of the development of seepage through the body and subsoil of the dam

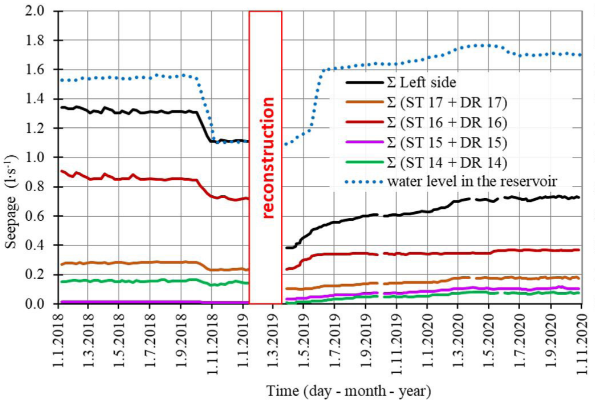

Fig. 5 *Development of seepage – left-hand drainage system*

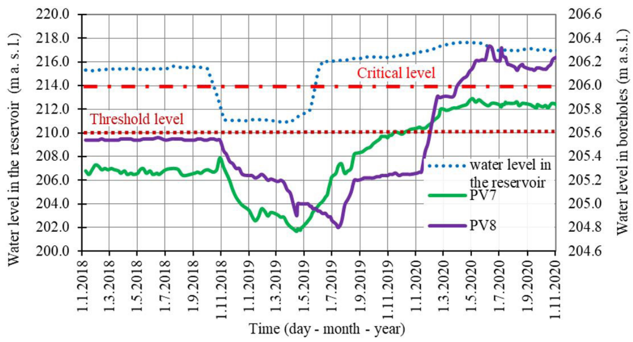

Fig. 6 *Development of the water level in the reservoir and in observation boreholes PV-7 and PV-8*

3 METHODS

The groundwater flow analysis was conducted using the finite element method (FEM), which enables the numerical simulation of steady-state and transient seepage with a free surface in earth dams. The mathematical formulation is based on the continuity equation combined with Darcy's law, thereby resulting in the governing partial differential equation for saturated–unsaturated flows (Fredlund and Rahardjo, 1993; Bear, 1972):

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q \;= S_S \frac{\partial h}{\partial t} \tag{1}$$

where

H total head (m),
k_x, k_y hydraulic conductivity in the x, y directions (m·s^{-1}),
S_S specific storage (m^{-1}),
Q boundary flux applied (m^3·s^{-1}/m^3),
t time (s).

The spatial domain was idealized as a two-dimensional vertical section under plane strain assumptions, which is appropriate when out-of-plane hydraulic gradients are negligible, and the dominant seepage mechanism is preserved (Gholami et al., 2025). The uniqueness and stability of the numerical solution depend on the proper specification of boundary and initial conditions, including seepage-face and phreatic surface definitions (Scudeler et al., 2017; VandenBerge, 2015).

The numerical solution was performed using GeoStudio software (Seep/W module, 2010), which applies FEM discretization with iterative determination of the phreatic surface and supports both saturated and unsaturated flow formulations (Shakouri and Mohammadi, 2020). The suitability of SEEP/W for embankment dam seepage analyses has been demonstrated in comparative and validation studies showing good agreement with physical modeling and alternative numerical approaches (Abdel-Kawy et al., 2021; Al-Janabi et al., 2024). Recent investigations further confirm that FEM-based seepage modeling reliably captures phreatic line development and discharge sensitivity in zoned earth dams (Mostafa and Zhenzhong, 2023; Pourbeirak et al., 2025).

3.1 Numerical modelling approach

Operational experience indicated that the development of the anomalous seepage in the left-hand part of the dam foundation was caused by local geological conditions. More permeable sandy soils occur at the foot of the left valley slope, which resulted in higher water levels in borehole PV8 compared to PV7, elevated filtration rates in PV3–PV5, and the accumulation of seepage in gauging shafts ST16 and ST17 (Fig. 3). These phenomena confirmed the underflow and lateral bypassing of the dam in its left-side connection to the valley slope.

To investigate this problem, the following methodological steps were applied:

- The design and verification of the numerical model in the PV6–PV8 profile, which was calibrated against the observed groundwater levels at a steady reservoir stage of 217.0 m a.s.l. in 2017. The model included the effect of seepage from the side tributary, which simulated lateral inflow from the PV3–PV5 profile.
- Design and verification of the numerical model in the PV3–PV5 profile, which was calibrated against the water levels measured at the same reservoir water level (217.0 m a.s.l.).
- The prediction of the development of the groundwater regime in both profiles at the maximum operating reservoir level of 218.6 m a.s.l., including an analysis of the interaction between seepage in the PV3–PV5 profile and lateral inflows to the PV6–PV8 profile.
- The simulation of remedial measures using a vertical cut-off wall. Different scenarios were modeled to evaluate its effects on the groundwater levels and seepage parameters at the maximum operating level of 218.6 m a.s.l. The parametric study assessed variations in the thickness of the wall and hydraulic conductivity.

4 RESULTS

4.1 Calibration of the numerical model in the PV6-PV8 profile

Based on the results of a geological survey, hydraulic conductivity values were assigned to the structural elements of the dam's subsoil (Fig. 7). The adopted values represent averages of the ranges measured and are summarized in Table 1. The variability of the M2 and M3 materials was not considered, as their effect on the groundwater regime in the dam body and subsoil (profiles PV6, PV7, and PV8) is negligible.

To obtain a satisfactory agreement between the calculated and observed groundwater levels in boreholes PV6, PV7, and PV8, it was necessary to define not only the hydraulic conductivity of the materials but also the effective length L and the associated inflow q representing seepage from the PV3–PV5 profile. The length L was tested at a range of 15 to 30 m. The boundary condition of the specific inflow values q was considered in a range of $9\cdot10^{-8}$ to $1.9\cdot10^{-7}$ $m\cdot s^{-1}$, and applied over the length L (Fig. 6). In the software, the inflows were introduced as filtration velocity values ($m\cdot s^{-1}$) multiplied by the chosen length. After several analyses, the length at which the inflow of water was finally activated was set at 27 m; the specific inflow quantity modelled of $1.5\cdot10^{-7}$ $m\cdot s^{-1}$ × 27 m corresponded to $4.05\cdot10^{-6}$ $m^2\cdot s^{-1}$.

Without simulating an additional inflow into the subsoil, the initial calculations showed that the groundwater levels calculated did not correspond to the in situ measurements in PV7 and PV8. In particular, the simulated values for PV8 were consistently lower than the in situ measurements. This confirmed the significant role of the relief drainage system, which effectively captures seepage through the PV6–PV8 profile but does not intercept water bypassing the dam along the left valley slope (Fig. 6).

Verification of the model was carried out using more than 20 variants for the PV6–PV8 profile. The results highlighted the sensitivity of the groundwater regime both to the hydraulic conductivity of the dam and foundation materials and to the parameters defining the lateral inflows from the left valley slope. The final configuration of the parameters input was adopted for subsequent parametric analyses. This verified model served as the basis for designing and optimizing remedial measures at the maximum operating reservoir level of 218.6 m a.s.l., with the objective of eliminating the anomalous seepage regime in the PV6–PV8 profile.

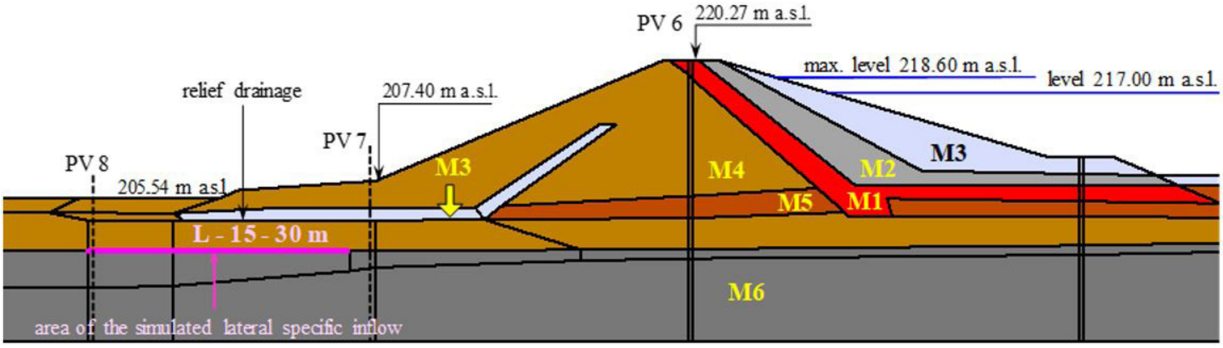

Fig. 7 Cross-section of the dam on the alluvial plain (PV6 – PV8)

Tab. 1 *Input data for the numerical model of the dam in the PV6-PV7-PV8 profile*

Material	Interface	Type of soil	Range k_f ($m\cdot s^{-1}$)	Chosen k_f ($m\cdot s^{-1}$)
M1	sealing + sealing carpet	Clay soils	$1\cdot10^{-8}$ – $5\cdot10^{-9}$	$5\cdot10^{-9}$
M2	upstream prism – transition zone	Silt sands	$1\cdot10^{-7}$	$1\cdot10^{-7}$
M3	upstream prism, drainage	Sandy-loamy gravel	$5\cdot10^{-5}$	$5\cdot10^{-5}$
M4	downstream stabilization prism and dam subsoil - Quaternary	Gravel-silt sands	$1\cdot10^{-7}$ – $2\cdot10^{-7}$	$2\cdot10^{-7}$
M5	horizontal sealing layer	Silty sandy, sands, silts	$1\cdot10^{-7}$ – $2\cdot10^{-7}$	$2\cdot10^{-7}$
M6	dam subsoil	Silt gravel	$1\cdot10^{-6}$ – $2\cdot10^{-6}$	$1\cdot10^{-6}$

4.2 Verification of the numerical model in the PV3-PV5 profile

The cross-section of the PV3–PV5 profile is shown in Fig. 8. The hydraulic conductivity values of the dam body soil were derived from the verification process in the PV6–PV8 profile. The composition of the dam subsoil was determined based on a geological survey and a longitudinal survey along the relief drainage system (Fig. 3). According to these results, hydraulic conductivities were assigned to the individual subsoil layers, which were then used for the verification of the numerical model.

The verification procedure focused on identifying the hydraulic conductivity values of the sandy soils in the dam subsoil that would yield an acceptable match between the calculated and measured groundwater levels in boreholes PV3, PV4, and PV5 in 2020, when the reservoir water level was relatively stable at 217.0 m a.s.l. Two variants were tested; i.e., with sand conductivity values of $4.0 \cdot 10^{-5}$ $m \cdot s^{-1}$ and $6.0 \cdot 10^{-5}$ $m \cdot s^{-1}$ (M4 material – Tab.1). Both solutions provided satisfactory agreement with the field data. The adopted composition of the PV3–PV5 profile (M5: $k_f = 4.0 \cdot 10^{-5}$ $m \cdot s^{-1}$) corresponds to a specific seepage of $2.03 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$ through the dam subsoil. Approximately 20% of this seepage is activated as lateral inflow, i.e., $1.05 \cdot 10^{-7}$ $m \cdot s^{-1}$, which is equivalent to $4.05 \cdot 10^{-6}$ $m^2 \cdot s^{-1}$ over a length of 27 m in the PV6–PV8 profile.

When evaluating the effect of the cut-off wall in the PV3–PV5 profile, the potential effect of the slope water was not considered, although it may have contributed to the groundwater levels observed in PV5. However, this simplification does not significantly affect the explanation of the anomalous regime in the PV6–PV8 profile or the design of remedial measures. The verified numerical model was therefore used in a parametric study at the maximum operating level of 218.6 m a.s.l. (Fig. 9), which provided the basis for optimizing measures aimed at eliminating anomalous groundwater conditions in the PV6–PV8 profile.

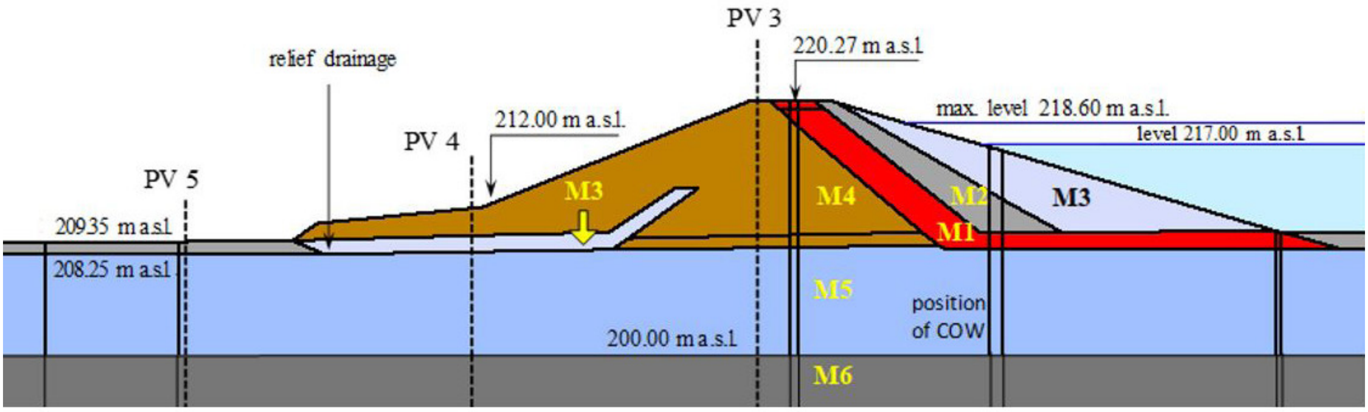

Fig. 8 *Cross-section of the profile of the dam in the valley stream profile (PV3-PV5)*

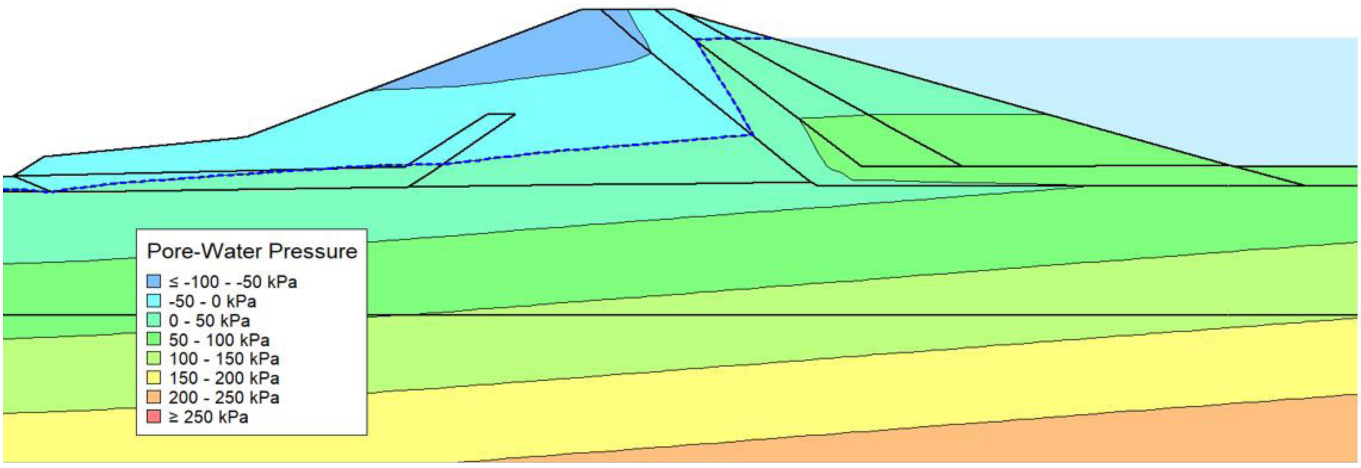

Fig. 9 *Results of the seepage analysis through the dam for the calibrated and verified numerical model – plot of pore-water pressures (PV3-PV5 profile)*

4.3 Solution and design of remediation measures

The design of the remediation measures was based on the verified numerical models of the PV6–PV8 and PV3–PV5 profiles. By incorporating their interaction, the spatial impact of the underflow and lateral bypassing of the dam was simulated, thereby focusing on the effect of the left valley slope on the groundwater regime in the alluvial plain (PV6–PV8). The principle of the numerical solution was the assumption that the total seepage through the PV3–PV5 profile ($2.03 \cdot 10^{-5}$ $m^3 \cdot s^{-1}$) directly affects the lateral inflow to the PV6–PV8 profile ($1.5 \cdot 10^{-7}$ $m \cdot s^{-1}$). These values were recalculated for the maximum operating reservoir level of 218.6 m a.s.l. and served as input data for the parametric study of the proposed cut-off wall. The methodological procedure for designing and optimizing the cut-off wall included the following steps:

- Evaluation of the seepage baseline: calculation of seepage through the PV3–PV5 profile (q_p) t 218.6 m a.s.l. without a cut-off wall, and comparison with the reference load state at 217.0 m a.s.l.; determination of the corresponding increase in the lateral inflow (q) to the PV6–PV8 profile.

- Prediction of the groundwater regime: simulation of the filtration parameters in the PV6–PV8 profile at 218.6 m a.s.l., considering the increased lateral inflow q, which corresponds to the specific seepage q_p from the PV3–PV5 profile.

- Cut-off wall scenarios in PV3–PV5: recalculation of seepage q_p through the dam subsoil at 218.6 m a.s.l. for different cut-off wall parameters (hydraulic conductivity and thickness; Table 2).

- Effect on PV6–PV8 profile: simulation of the groundwater regime with a cut-off wall in the PV3–PV5 profile, considering the reduced lateral inflow q derived from the modified seepage q_p.

This parametric study enabled the evaluation of various cut-off wall configurations and their effectiveness in reducing groundwater levels, seepage discharges, and hydraulic gradients in the most critical part of the dam subsoil. The results of the numerical simulations of the groundwater and seepage parameters, which were obtained by the methodological procedure described, are summarized in Table 2. The table presents the seepage values calculated through the dam subsoil in the PV3–PV5 profile (q_p, expressed per meter of length) together with the corresponding specific lateral inflows (q) to the PV6–PV8 profile. In addition, Table 2 shows the simulated groundwater levels in boreholes PV6–PV8, which are compared against their defined limit and critical values.

The results clearly demonstrate the positive effect of a cut-off wall on reducing groundwater levels and seepage in the area of the dam examined. A comparison of the variants tested shows that a cut-off wall with a hydraulic conductivity of $1.0 \cdot 10^{-8}$ $m \cdot s^{-1}$ provides a greater reduction in seepage and groundwater levels than a wall with $1.0 \cdot 10^{-7}$ $m \cdot s^{-1}$. For instance, a cut-off wall with $k_f = 1.0 \cdot 10^{-8}$ $m \cdot s^{-1}$ and a thickness of 0.6 m achieved a more significant improvement than a wall with $k_f = 1.0 \cdot 10^{-7}$ $m \cdot s^{-1}$ and a thickness of 1.0 m.

Figure 9 illustrates the relationships between the groundwater levels only in borehole PV8 and the seepage values in the PV3–PV5 profile for the different cut-off wall variants. The simulations indicate that the hydraulic conductivity of the wall has a stronger effect on efficiency than its thickness. In addition, the risk factors related to the filtration stability, such as the seepage rates and hydraulic gradients, were analyzed. These parameters were significantly reduced by the introduction of a cut-off wall; they reached values below the critical thresholds and thereby eliminated the risk of suffusion and internal erosion in the affected area.

Tab. 2 *Results of the parametric study - at a maximum operating level of 218.60 m a.s.l.*

Alternative $k_{f,COW}/b_{COW}$	q_p ($m^2 \cdot s^{-1}$)	q ($m^2 \cdot s^{-1}$)	H_{PV6} (m a.s.l.)	H_{PV7} (m a.s.l.)	H_{PV8} (m a.s.l.)
without COW	$2.41 \cdot 10^{-5}$	$1.77 \cdot 10^{-7}$	209.35	205.92	206.66
07/0.6	$9.80 \cdot 10^{-6}$	$7.20 \cdot 10^{-8}$	209.03	205.19	205.32
07/0.8	$8.32 \cdot 10^{-6}$	$6.11 \cdot 10^{-8}$	208.99	205.11	205.12
07/1.0	$7.29 \cdot 10^{-6}$	$5.36 \cdot 10^{-8}$	208.97	205.05	204.99
08/0.6	$3.68 \cdot 10^{-6}$	$2.71 \cdot 10^{-8}$	208.88	204.78	204.46
08/0.8	$3.22 \cdot 10^{-6}$	$2.37 \cdot 10^{-8}$	208.87	204.76	204.39
08/1.0	$2.91 \cdot 10^{-6}$	$2.15 \cdot 10^{-8}$	208.86	204.73	204.34
Cut-off value (H_{MH})			**212.50**	**205.70**	**205.60**
Critical value (H_{KH})			**214.80**	**206.50**	**206.00**

Note: cut-off wall parameters - 07/0.6 = COW hydraulic conductivity ($k_{f,COW}$) is $1 \cdot 10^{-7}$ $m \cdot s^{-1}$, and COW thickness (b_{COW}) is 0.6 m.

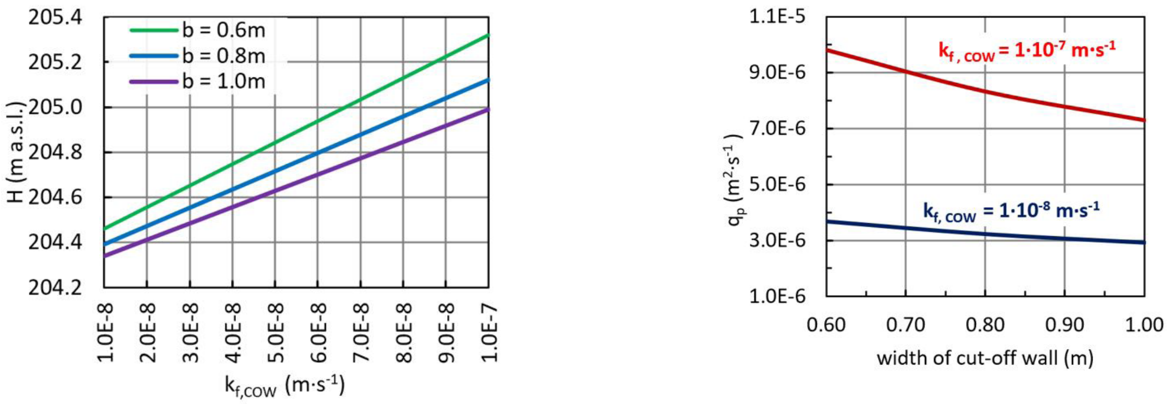

Fig. 10 *Effect of the hydraulic conductivity of the cut-off wall and its width on a) the development of the levels in the PV-8 boreholes. b) the development of seepage in the dam's subsoil in the profile PV3 - PV5 at a maximum operating level of 218.60 m a.s.l.*

5 DISCUSSION

The results of the parametric study confirmed that the construction of a cut-off wall is an effective measure for mitigating seepage-related risks. In zones with semi-permeable to permeable sandy soils, particularly in the left-hand part of the dam body and its foundation (boreholes PV2, PV3, PV4, PV5, and PV14), the following improvements were observed:

- specific seepage through the subsoil on the left side (q_p) was significantly decreased, which in turn reduced the associated lateral inflows (q) toward the PV6–PV8 profile,
- the water levels in the PV7 and PV8 observation boreholes dropped below both the limit and critical thresholds, thereby eliminating a key factor that threatened the structural stability of the dam,
- hydraulic gradients in soils prone to suffusion were reduced to values below the critical range I_{crit} = 0.1–0.4 (Istomina, 1957), which ensured the stability of the filtration.

These findings highlight the strong effect of local geological heterogeneities on a seepage regime. The effectiveness of the cut-off wall confirms that the targeted structural measures can compensate for unfavourable geological conditions and restore the safety of a dam. Significantly, the simulations also showed that the hydraulic conductivity of a wall has a greater effect on its efficiency than its thickness, which has practical implications for the cost-effectiveness of remediation designs.

Nevertheless, several limitations must be acknowledged. The results are site-specific, which reflects the geological composition and operational conditions of the dam. The potential contribution of the slope water to the groundwater levels, particularly in borehole PV5, was not explicitly considered in the modeling, which introduces some uncertainty into the results. In addition, the study addressed steady-state conditions; long-term monitoring is required to verify the sustainability of the proposed solution under variable hydrological loads. Despite these limitations, the study demonstrates a methodological framework that combines monitoring data with numerical modeling to design effective remedial measures. This approach is applicable to other earthfill dams with comparable geological conditions, thereby offering practical guidance for dam safety management.

For existing dams, cut-off walls represent an advantageous solution because they can be implemented without the need for major reconstruction of the dam body. They directly target the critical seepage paths in the subsoil and valley slopes, while minimizing interventions into the operational structure. In comparison to alternative measures such as complete replacement of a drainage system or reconstruction of the upstream sealing, cut-off walls are technically less invasive, more cost-effective, and can be designed to address localized geological anomalies. This makes them a particularly suitable option for remediation of older dams where continuous operational and safety assurance are required. Future research should focus on validating the long-term performance of cut-off walls, assessing their effectiveness under extreme hydrological events, and refining models to better account for transient groundwater dynamics.

6 CONCLUSIONS

The analysis of the Lozorno Dam confirmed that the anomalous seepage regime was primarily caused by the occurrence of locally permeable sandy soils on the left valley slope and its foundation. The numerical simulations demonstrated that the introduction of a cut-off wall in this area represents an effective remedial measure that improves the seepage regime and supports the overall safety of the dam.

An innovative aspect of this study lies in the integration of long-term monitoring data with finite element modeling to identify the mechanisms behind the observed anomalies and to design targeted remedial measures. Although seepage in the dam foundation is inherently a three-dimensional phenomenon, the key mechanism at the site of the case study could be captured using 2D cross-sectional FEM models by prescribing a calibrated lateral inflow boundary condition derived from the adjacent profile, which effectively represents out-of-plane bypass flow from the left valley slope. The parametric study of the cut-off wall variants provided an important insight: the hydraulic conductivity of the cut-off wall has a stronger impact on efficiency than its thickness, which has direct implications for the optimization and cost-effectiveness of remediation strategies.

From a practical perspective, the study offers a methodological framework for the assessment and rehabilitation of small earthfill dams under complex geological conditions. Although the findings are specific to the dam, the approach of combining detailed field monitoring with numerical modeling can be applied more broadly to support dam operators and designers in selecting appropriate safety measures.

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