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Estimation of Water Infiltration at a Given Embankment Dam with Sealing Deficiencies by a 3D Numerical Model

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Abstract: *The paper presents a way of studying the water infiltration at the Motru embankment Dam (river ballast fill, clay core sealing) by a 3D numerical model covering the deficient right supporting bank. Since due to sealing imperfections the reservoir runs under level restrictions, the calculations were performed in two stages. First, the model was set up and checked for the existing running situation and then it was endowed with a proposed supplementary ground sealing element that would allow the reservoir running at its designed full capacity. The final goal of the study would be to estimate the maximum appropriate value of the water exfiltration discharge for a dam safety operation under the load given by the originally designed water level. This parameter may than be considered as representative for the expected deep sealing quality, under the required condition of accepting an exfiltrated water turbidity below the value pointed out by stored water.*

Keywords: *Embankment dam, core sealing, ground sealing, water infiltration, numerical modelling.*

1. Motru dam – general description

The Motru Dam on Motru River in Gorj County, Romania, is a ballast-fill embankment sealed with a clay core (figure 1), with a maximum height of 48 m with respect to the foundation level [1,2]. The dam crest is situated at 484.00 mSL and the reservoir usual operation water level is designed at 480.00 mSL. The high-waters are to be discharged by a funnel spillway and eventually by the bottom outlet, both driven by the left supporting bank. As part of the complex Cerna-Motru-Tismana-Bistriţa Water Development, the main purposes of Motru water reservoir are energy production at Tismana Hydro-Power Station and water supply of downstream towns.

The foundation ground in the streambed and towards the left bank shows the fundamental supporting layer – crystalline rock of low permeability and moderate cracking – close to surface, while for the right bank it leaves space for alluvia thick deposits of various granulometries and of larger permeability coefficient (figure 2).

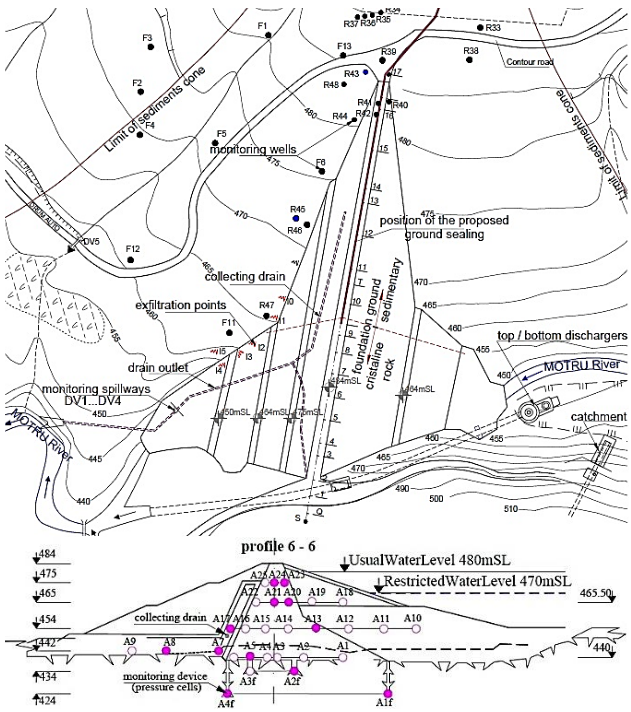

Fig. 1. Motru Dam – overview and cross section

After a short period from the moment of entering into operation in the year of 1983, important water exfiltration was noticed at the dam (producing also transport of fine material) and consequently water level constraint had to be imposed at 470.00 mSL. It was further on perceived that the water infiltration from reservoir happened predominantly by the right bank terrace, at a relatively high permeability ratio ranging from 0.5 to 50 m/day. Several field studies were performed throughout time, proving that exfiltration come mainly from the reservoir by the superficial layers of the right bank under- and side-passing the sealing core, layers not properly sealed during the accomplishment of the retaining structure.

The Institute Studies and Projects in Hydropower developed in 2006 a rehabilitation documentation that proposes the accomplishment of a continuous slurry wall imbedded into the fundamental supporting layer. Driven from the dam crest, the wall was estimated at a total surface of about 10900 m^2 [2]. The project was revised, so the final solution assumes now the foundation ground sealing on the streambed and the right supporting bank.

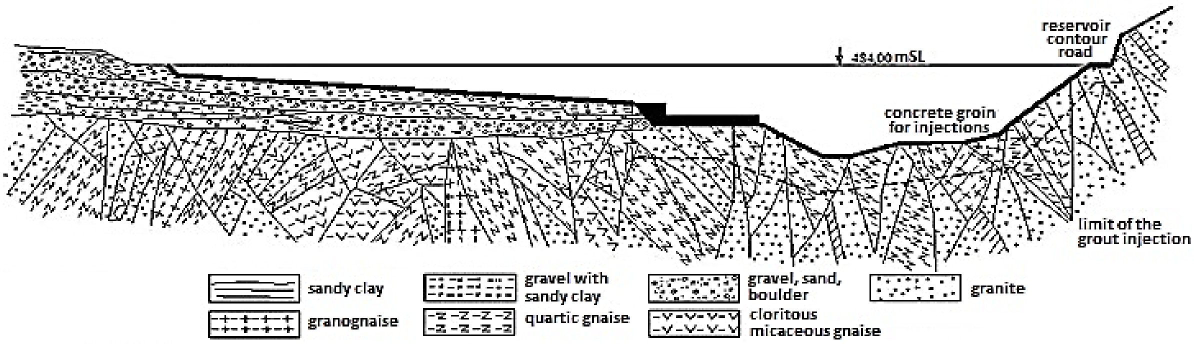

Fig. 2. Valley profile along the Motru Dam axis showing the general geological layer disclosure

In order to develop the infiltration numerical model focusing the right side of the dam and its foundation ground, as according to the revised rehabilitation solution, a three-dimensional volume (figure 3) following a given geometrical configuration was sliced from the entire space of the dam emplacement [3]. The execution quality of the proposed ground sealing could be checked by the help of a numerically estimated acceptable value for the water exfiltrated discharge under a load provided by the originally designed usual retaining water level in the reservoir. This acceptable limit to be assessed by the developed numerical model will have to fulfil the specific condition of an exfiltrated water turbidity below or at most equal to its level in the reservoir.

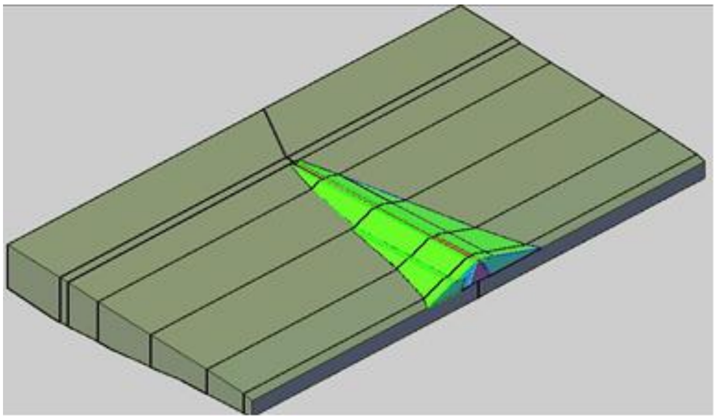

Fig. 3. General geometrical configuration of the modelled dam - emplacement ground domain considered from the streambed towards the right bank

2. Development of the dam - emplacement ground numerical model

The three-dimensional model was obtained by meshing the considered domain by employing SOLID70 thermal type 3D finite elements (figure 4) offered by ANSYS software package [4].

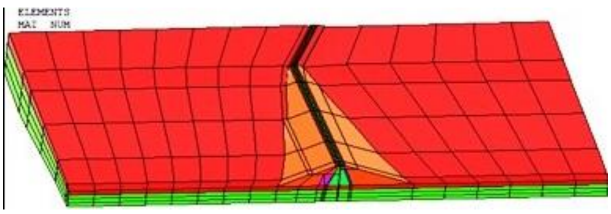

Fig. 4. 3D meshed domain, dam - emplacement ground according to the revised rehabilitation solution

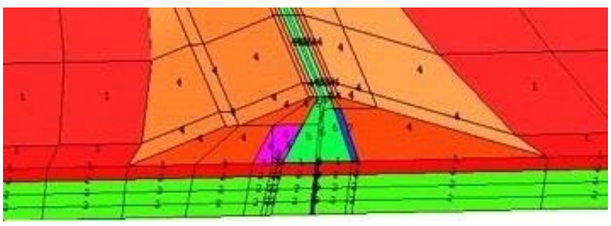

Fig. 5. Detailed view of the Motru Dam central zone indicating the materials' codes

The given values of the permeability coefficient corresponding to the involved materials (supporting ground and embankment fill, [2]) are presented by table 1. Figure 5 brings a zoomed-in view that points out the materials' codes and the modelled downstream draining element. The collecting drain at the bottom of the downstream filter is accomplished by a prefab pipe of 0.80m in diameter encased in a perimetrical concrete massive of square cross section of 1.50m in side. The concrete element is perforated so to collect the infiltrated water and gravitationally discharges by a monitored outlet placed along the streambed.

Table 1: Engaged permeability coefficients for the involved materials

Crt. no.	Type of material	Permeability coefficient, k	
		m/sec	m/day
1	gravel-sand-boulder	0.0001	8.64
2	alluvia deposits	0.0025	216.00
3	sealing screen 1	1.0e-5	0.864
4	embankment fill	0.000347	29.98
5	clay core	1.0e-8	0.000864
6	downstream filter	0.0005291	45.72
7	upstream filter	0.000012	1.0368
8	drainage equivalent -step1 drainage equivalent -step2	0.00615 0.9419	531.50 81380
9	sealing screen 2	2.0e-7	0.0216
10	sealing screen 3	0.0004	34.56
11	sealing screen 4	0.0002	17.28

The automatic mesh of the designed domain led to a model of 1373 finite elements (SOLID70 with 8 joints) and 2094 joints. The numerical simulation of the unsteady regime model engaged a time step of 1 day to consider the storage water level fluctuation and a time step of ½ day to perform the iterative calculations [5]. The boundary conditions are given by water level fluctuation at a number of specific joints – on the dam upstream face, at the wells on dam downstream part and at the equivalent drain, respectively.

2.1 Adjustment of the numerical model for the transitory regime

Given the entire available data base represented by the water level time development in the reservoir and several monitoring wells driven on the right mountainside downstream and aside of the retention structure (F1, F5, F6, F11, F12, R35) together with the water discharge values at the monitoring spillways DV3 and DV4 on the outlet of the infiltrated waters collector (equivalent drain), a total time interval of 4748 days – from January 1st, 1990, to January 1st, 2003 – was considered for running the numerical model (see figure 1). It was noticed from the supplied data that usually there is no recorded information for nonworking days (weekends and other official holidays). By eliminating these blank moments, a total number of 2274 days remained to perform the analysis.
The infiltration (permeability) coefficient for the modelled collecting drain k_{equiv} is initially unknown, following to be revealed by the numerical model adjustment operation. The properly corresponding final value shall be established by successive tests until the infiltrated discharge values reached by the numerical analysis come to match with the measured ones (Q_{total} = DV3+DV4). The setting operations were initially performed for the 2274 days time interval and it was noticed that for the beginning period, when the reservoir water level is usually above 475mSL and the measured infiltration discharge varies between 50 and 15 l/s, the computed discharge values come close to the measured ones. By the other hand, for the ending period, when the reservoir level is below 474mSL and the infiltrated measured discharge goes from about 10 to 0.5 l/s, the numerical model leads to values spreading away from the target ones.

As considering the downstream drain outgoing part, its hydraulic head is known as equal to the geometrical level 463.85mSL of the joints attached to it (1053, 1054, 1063 and 1064). Still, this condition would match to the numerical model only if the equivalent drain runs as a pipe at full cross section flow. In the situation that the drain operates under a free level flow regime with partial filled cross section (as it happens towards the ending part of the considered time interval), the outgoing water level would result from the model as variable below the specified geometrical level. Artificially, for the situation of low outgoing discharge values (as when Q_{total} = DV3+DV4 tends to range from about 10 to 0.5 l/s – happening mainly along the 2001…2002 period), a new specific equivalent permeability coefficient (k_{equiv1}) was established – drainage equivalent 1 in table 1 – so that the modelled pipe to run at full flow. As a consequence, the 3D numerical model adjustment for a transitory operating regime had to follow two steps:

Step 1 – the equivalent drain running as a pipe under a free level flow regime with its cross section partially filled. There was engaged the k_{equiv1} value while the permeability coefficients describing materials 9, 10 and 11 that model the sealing element were successively altered till the outgoing total infiltrated discharge came out in the range of the corresponding measured values. The three finally estimated values by this first step are to be further on considered as fixed for the second step.

Step 2 – the equivalent drain running as a pipe under a free level flow regime at full cross section. A k_{equiv2} value was then successively adjusted looking to have a fit on the total outgoing infiltrated discharge values. When this condition was fulfilled, the reached k_{equiv2} value was assumed as fixed for the model.

In explicit terms, by considering for step 1 the time interval from January 9, 1997, to December 22, 2002, (meaning from day 1352 to day 2274) with its specific boundary conditions – the water level development at joints attached to dam upstream face (reservoir) and to the wells F1, F5, F6, F11, F12 and R35, and respectively the fixed level of 463.85mSL at the joints attached to drain outgoing (1053, 1054, 1063, 1064) – and proceeding as described to several adjustment numerical computations, the three proper values of permeability coefficients describing the sealing element were revealed and so fixed for the model (as presented by table 1). The representative phenomenon time dependent parameters are then graphically presented for the significant final stage of adjustment step 1 (figures 6a, 7a and 8a).

The values representing the time developments showed in figures 7 and 8 were saved in an outgoing file in order to acquire a correlated development as expressively presented by figure 9, from day 1852 to day 2202.

Afterwards, the time interval from April 27, 1993, to December 23, 1996, (meaning from day 750 to day 1352) was considered for step 2 adjustment operation. By engaging the corresponding boundary conditions (as previously mentioned) and by performing the adjustment operation described for this second step, the proper drain equivalent value k_{equiv2} was established for the modelled drainage (see table 1). After concluding the second adjustment step operation, the representative time dependent parameters were graphically processed (figures 6b, 7b and 8b). The values characterizing time developments in figures 7b and 8b were additionally processed in order to obtain the correlated development presented by figure 10, from day 750 to day 1350 (as ignoring the first 750 days with no registered data at well R35).

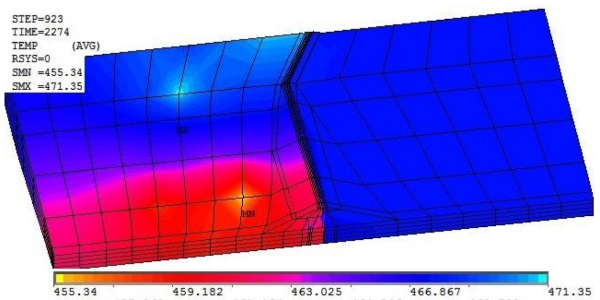

Fig. 6.1 Hydraulic head development at the end of the adjustment step 1 period – day 923 (December 22, 2002), corresponding to a water level of 467.79mSL in the reservoir

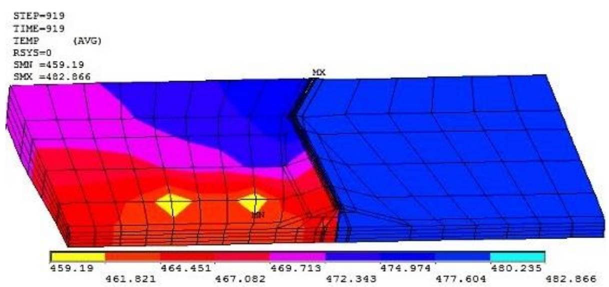

Fig. 6.2 Hydraulic head development on day 919 (April 10, 1994) after the adjustment step 2, corresponding to a water level of 480.00mSL in the reservoir

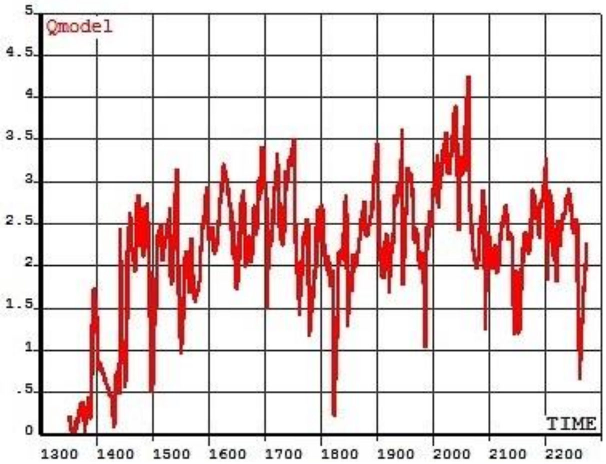

Fig. 7.1 Computed infiltration discharge (DV3+DV4) time development along the adjustment step 1 period of 922 days

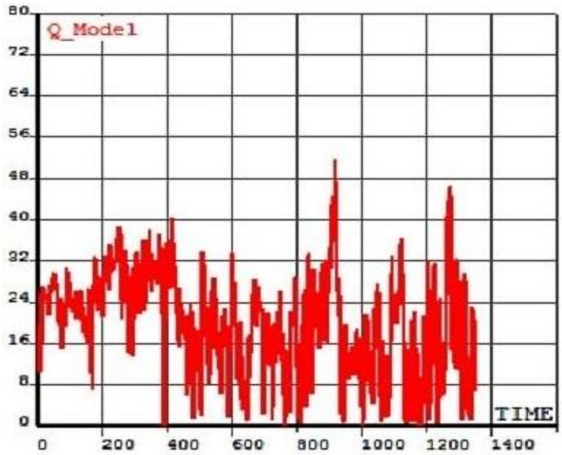

Fig. 7.2 Computed infiltration discharge (DV3+DV4) time development along the adjustment step 2 period of 1352 days

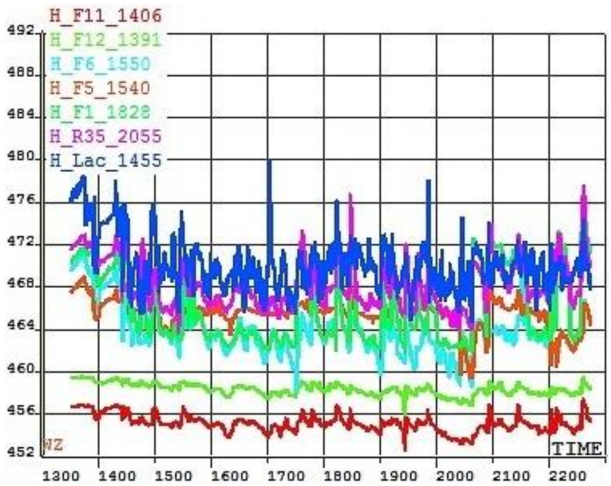

Fig. 8.1 Water level time development in the reservoir and at the six wells along the adjustment step 1 period of 922 days

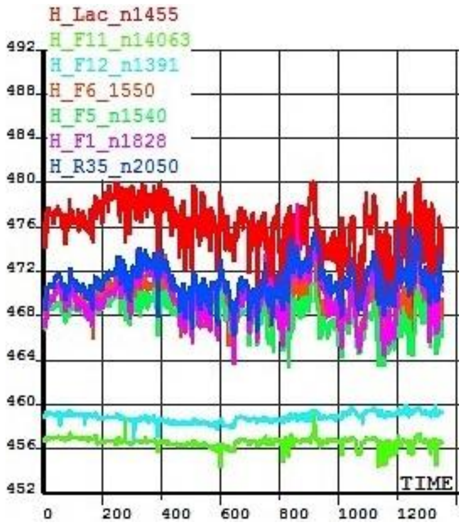

Fig. 8.2 Water level time development in the reservoir and at the six wells along the adjustment step 2 period of 1352 days

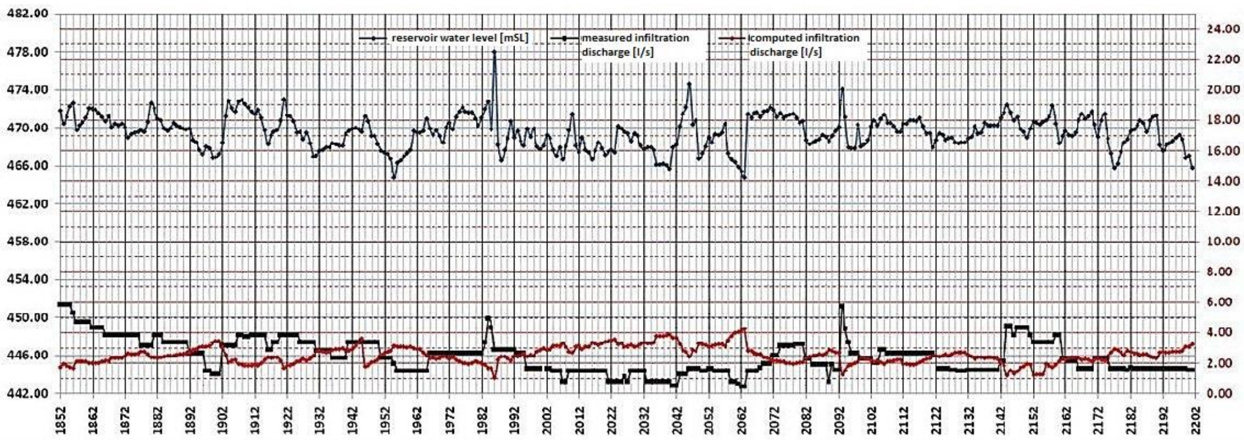

Fig. 9. Correlated time development of Motru reservoir water level and measured/computed total infiltration discharge (DV3+DV4) after the adjustment step 1 (from September 6, 1999, to October 5, 2001)

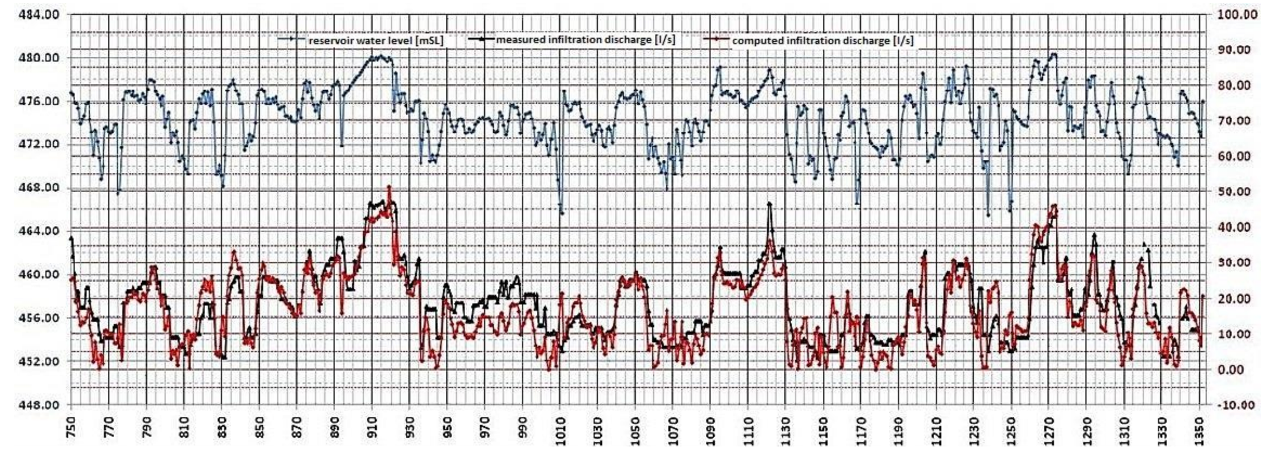

Fig. 10. Correlated time development of Motru reservoir water level and measured/computed total infiltration discharge (DV3+DV4) after the adjustment step 2 (from April 27, 1993, to December 23, 1996)

Studying the numerically reached time development with respect to the measured one (as presented by figure 10), there was accepted that the numerical model of Motru Dam is appropriately adjusted for performing further analysis.

2.2. Infiltrated discharge under transitory running regime during the time period January 3, 2012, to December 24, 2013

The adjusted model behaviour was afterwards examined by running an analysis over a later time period. There was going to consider the time interval of 286 days from January 3, 2012, to December 24, 2013, which is lacking data regarding the measured infiltration discharge at monitoring spillways DV3 and DV4. The equivalent drain would work mainly as a pipe under a free level flow regime with its cross section partially filled. The boundary conditions would refer to the registered water level development in the reservoir and F5, F6, F11 and F12 wells, and the 463.85mSL value fixed for the four joints (1053, 1054, 1063, 1064) attached to the drain outgoing, respectively. The main time dependent parameters – hydraulic head at a given moment (figure 11) or water levels and infiltration discharge – obtained by running the numerical analysis may be correspondingly draw out. A correlated reservoir water level and infiltrated discharge developments with respect to time is given by figure 12 obtained by postprocessing the numerical values.

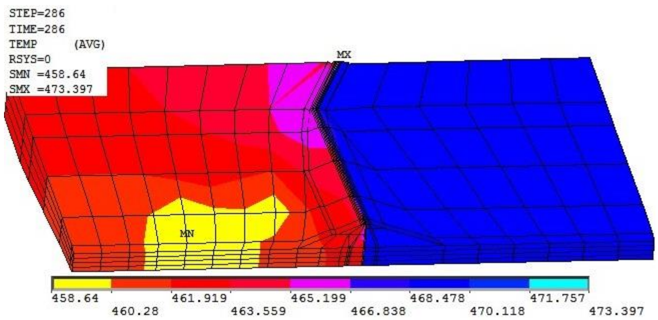

Fig. 11. Hydraulic head development on day 286 (December 24, 2013), corresponding to a reservoir water level of 470.09mSL

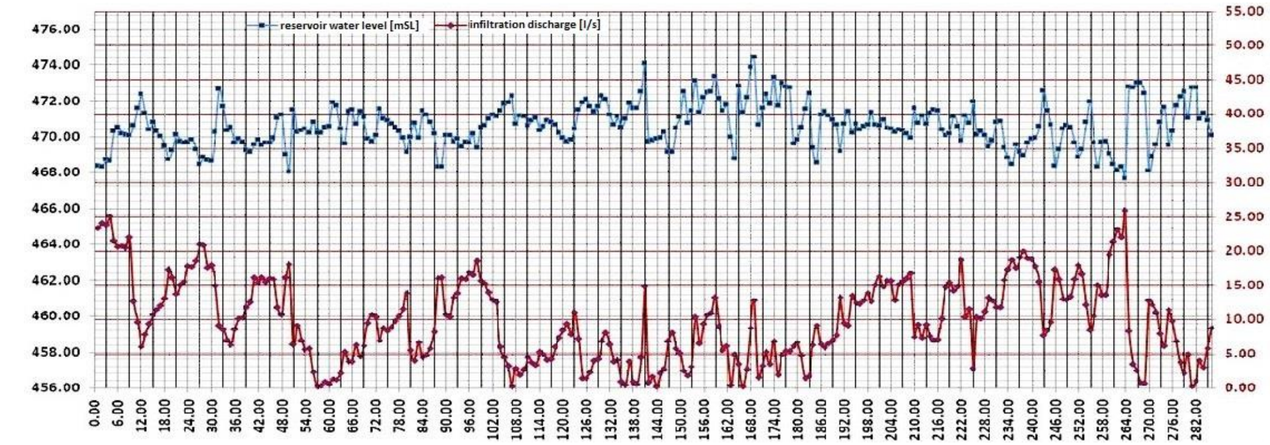

Fig. 12. Correlated time development of Motru reservoir water level and computed total infiltration discharge (DV3+DV4) along the 286 days period of missed registered data (from January 3, 2012, to December 24, 2013)

3. In depth additional sealing at Motru Dam – exfiltrated discharge under transitory regime

As already mentioned, the Institute for Studies and Projects in Hydropower developed in 2006 a documentation that proposes for Motru Dam the accomplishment of a continuous slurry wall driven from the dam crest, going through the deficient underground sedimentation strata and imbedded into the fundamental supporting layer [2]. It was concluded soon after that this additional sealing element should continue the dam core in the ground only from the streambed along the right supporting bank. In order to estimate the infiltration phenomenon that develops mainly by the right side of the barraged section, the previously adjusted numerical model (k_{equiv2} = 0.9419 m/s = 81380 m/day) was endowed with a sealing screen following the proposed geometry and quality. For the new numerical analysis, the defining permeability coefficient of the finite elements in the affected area was accordingly modified [3]. Specifically, the already built elements representing now the designed slurry sealing screen – assigned materials 9, 10 and 11 as indicated in table 1 – are assumed to show a permeability coefficient of k_{screen} = 3.0e-8 m/s = 0.002592 m/day. The detailed views in figure 13 show, beside the already discussed model of the equivalent drain, the modelled configuration of the foreseen sealing screen.

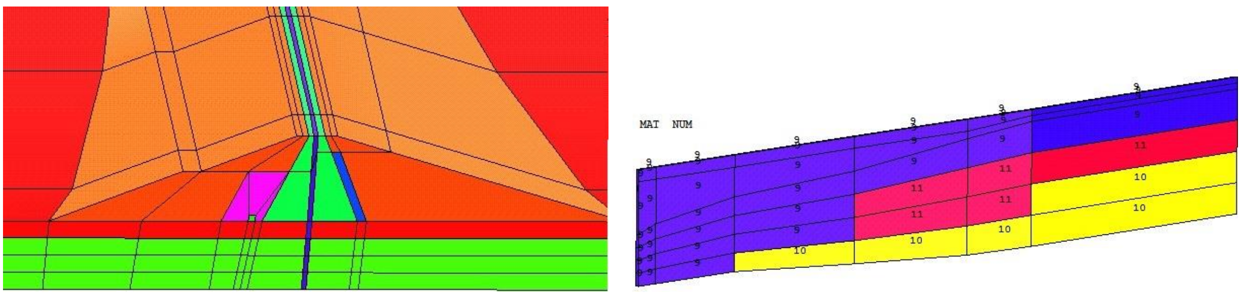

Fig. 13. Detailed view of the Motru Dam central zone endowed with the designed sealing screen (left); profile of the underground sealing screen driven through the right bank indicating the materials' codes (right)

There are further on presented the numerical analysis results for two of the three significant time periods previously considered in the model adjusting stage, meaning from April 27, 1993, to December 24, 1996, and from January 3, 2012, to December 24, 2013, respectively.
The equivalent drain works as a free flow pipe (of an enforced hydraulic head 462.45mSL) and the boundary conditions are represented by the water level time development in the upstream reservoir and several monitoring wells driven downstream on the right bank (the available data at F1, F5, F6, F11, F12 and R35 for the first time period and at F5, F6, F11 and F12 for the second period), and also an enforced water level of 462.45mSL for the joins attached to the drain outgoing. This outgoing level value was reached by several successive alterations in order to fulfil a proper

correlation also during intervals of significant hasty variations of the reservoir water levels (a variation in the total outgoing infiltration discharge would correspond to a previous variation in the reservoir level). The eloquent analysis results would refer to the water head development at a given moment (figures 14) and the total outgoing infiltration discharge at the monitoring spillways DV3+DV4 in correlation to the reservoir and monitoring wells water levels behaviour with time (figures 15). The correlated developments are shown as suggestive over a reduced number of days (602 for the first mentioned time period and 286 for the second one) for which continuous reliable data were available.

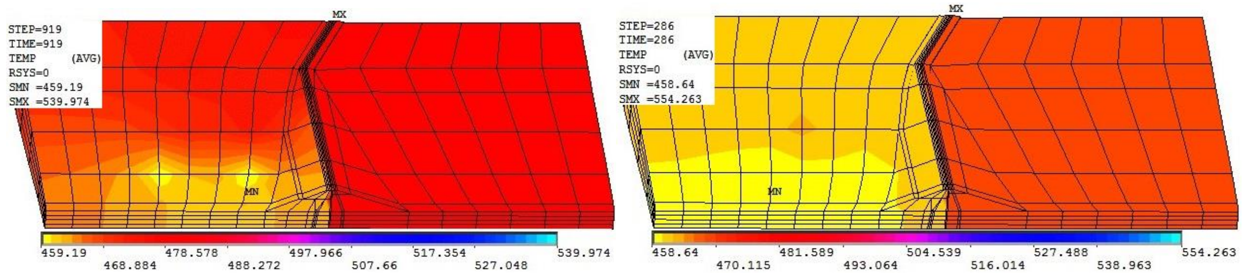

Fig. 14. Estimated hydraulic head development in case of a slurry sealing wall accomplishment – on April 10, 1994, corresponding to 480.00mSL in the reservoir (left) and on December 24, 2013, corresponding to 470.09mSL in the reservoir (right)

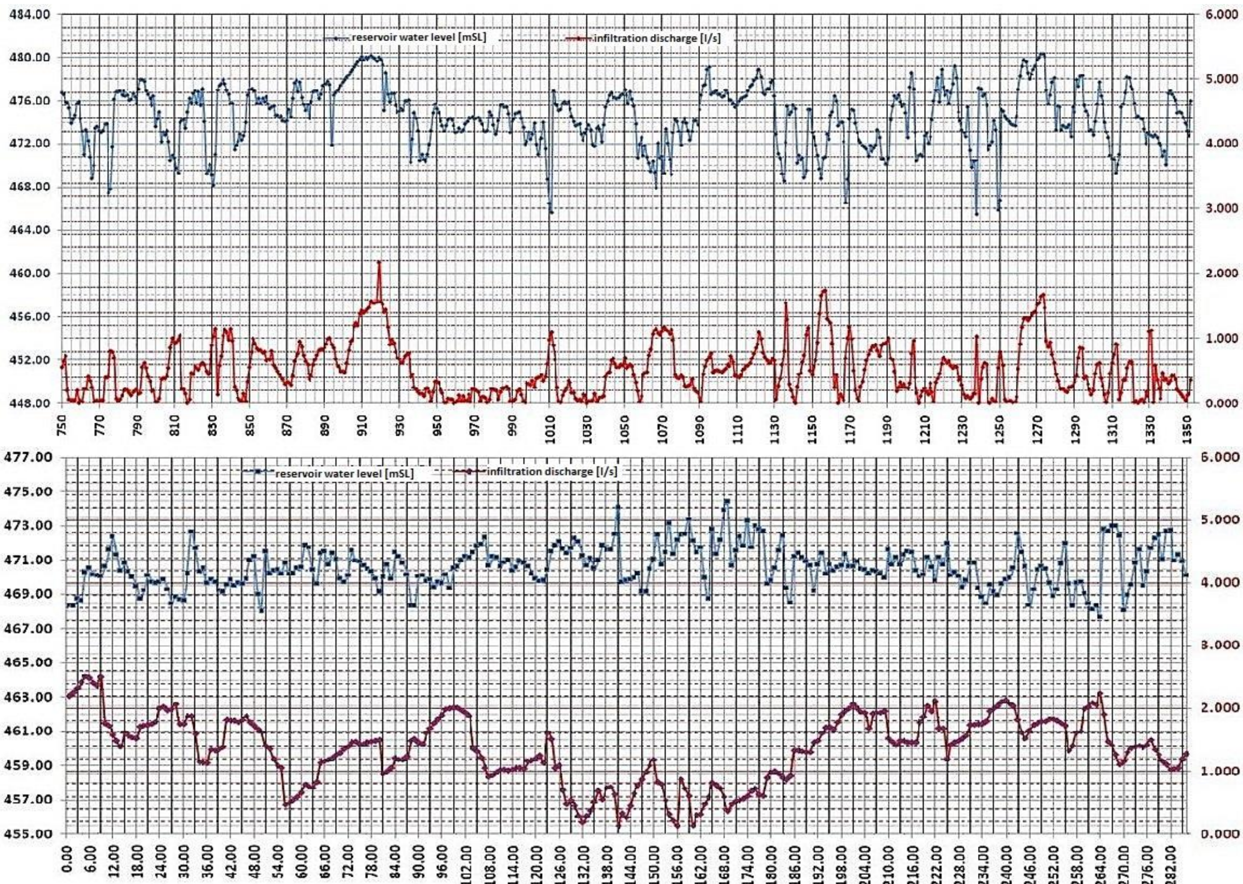

Fig. 15. Correlated time development of Motru reservoir water level and computed total infiltration discharge (DV3+DV4) along the 602 days in-between April 27, 1993, and December 24, 1996, and along the 286 days in-between January 3, 2012, and December 24, 2013 (below), for the retaining structure with designed additional sealing screen

By searching along the numerical data behind the time developments in figures 15, one would notice that the total maximum infiltrated discharge at drain outgoing in the situation of additional sealing screen accomplishment might range from about 2.17 to 2.51 l/s.

4. Conclusions

There can be assumed that throughout the long dam operating period of almost ten years (March 29, 1993 – December 24, 2013) a significant material transport was produced, specifically the fine material from the underground area in the supporting right bank considered to be sealed by the slurry screen. It is also estimated that water level operation constraint at 472.00mSL and shortly after at 470.00mSL determined a reduction in the scouring phenomenon.
As about the rehabilitation solution, by accomplishing an additional sealing element through the dam core and its under side poor sedimentary strata on the right supporting bank, there is estimated that in case the restriction level around 470.00mSL is maintained the total infiltration discharge would go at most to about 2.51 l/s, meaning about ten times less than the existing un-interfered situation.
Assuming the accomplishment of the proposed sealing screen, different procedures can be further on employed to reach an estimation of the infiltration discharge development in time corresponding to an operation reservoir water level around the initially designed value of 480.00mSL, either by altering the available reservoir level data and model rerunning or by numerical extrapolation of the already reached results for the restricted level. A satisfying indicative estimation of the mean infiltration discharge value can be obtained by analysing the built numerical model under a stationary regime given by the usual water level at 480.00mSL.
Proceeding to a numerical extrapolation of the values corresponding to the analysed situation of around 470.00mSL restricted level, there was estimated an amplification ratio of about 3.06 for the infiltration phenomenon in case of increasing the operation reservoir water level at around 480.00mSL. The total infiltration discharge would go under this circumstance at a maximum value of about 7.67 l/s, meaning in the range of the forecasted value (Popovici & Ilinca, 2016) of 7.04 l/s.

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