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Hydraulic investigation of flood defences using analytic and numerical methods

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The aim of this paper is presenting case studies of hydrodynamic modeling of flood control dams. The SEEP2D module of Groundwater Modeling System package was used successfully for solving different case-study problems. The purpose of the analysis was to determinate the amount of seepage through flood control dams with different features. The results of the study can provide useful assistance for specialists in floodwater prevention and protection. The comparison of the numerical and analytical data proved the reliability and accuracy of the SEEP2D module for flood control dam simulations.

Key words*: dam, hydrodynamic modeling, GMS, SEEP2D, floodwater*

Introduction

There has been an increasing social interest in the fight against the damage caused by floods due to Hungary's natural and geographical location [1]. Because Hungary occupies the lowest parts of the Carpathian basin (Fig. 1), which consists of mostly flat regions, it is virtually exposed to flood dangers as rivers from the surrounding regions of the Alps and the Carpathians rush down the mountains, it is necessary to fight against the flooding of rivers.

Fig. 1. The Danube river basin [2].

One fifth of the country (21 000 km^2 out of the 93 031 km^2) is protected by river embankments and flood protection dams from the floods [3]. The 4 200 km-long flood barrier and river embankment system mostly built in the XIX. century protects 30 % of Hungary's population, 32 % of railway lines, 15 % of roads. It also provides protection for 2 000 industrial facilities and 18.000 km^2 strategic agricultural lands and their crops. That's why it is important to maintain flood protection dams regularly, it needs multifunctional examination to avoid any damage caused by floods [4].

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Today's modern modeling methods enable us to use efficient computer simulations for checking, design and maintenance work. István Völgyesi's article published in 2008 gave a nice example for dam simulations using the finite difference MODFLOW [5] module. In order to use effectively the modeling approach, one has to know the hydrodinamical and hydraulical features of water leaking through the dam as well as the geometrical parameters of the investigated dams.

Völgyesi [5] used the Processing Modflow computer program to give the hydraulical and flow behavior of dams, while in our case the Groundwater Modeling System program package with the finite element SEEP2D module was applied for computer modeling to examine three typical flood protection dams (all on the area of the North-Hungarian Environmental and Water Authority) as well as a reservoir dam (the dam of Lázbérc reservoir). At the Lázbérc dam there were measurements of leakage yields, so we had the opportunity to compare the results on simulated and the actual field data.

The importance of flood defences, leakage through the flood defence

Most of the main flood protection dams are made of earth in Hungary. What we can see nowadays of our flood defences is the result of many constructional phases. According to the changing pattern of floodwater there have been developments in the cross section of flood protection dams. Thanks to these changes the internal structure of these flood defences are very varied [6].

The rising floodwater -due to the mounting water pressure - tries to get into the flood defence and to the subsoil. Since there is no absolute watertight soil, the pores of the material of the flood defence is filled with water up to a certain level and moves towards the defended side. It happens sooner or later, it is only a matter of time. There are several analytical calculation methods for determining the upper level of leaking water in the case of homogenous flood defences but it is well known that homogenous flood defences are very rare in real life situations [7].

Analytical leakage calculations of inhomogenous flood defences also exist [8]. However these methods are rarely applicable in practice and they are full of mistakes.

Leakage at the bottom and at the layers is a typical phenomenon of layered dams, which is a result of inhomogenity. Leakage is a naturally occurring process so it happens sooner or later in any case. But it has no significance in terms of durability if there is a short flood, if the material of the dam is quite watertight, or if there is a back-dam made of suitable granular material [8]. It starts to become dangerous if the whole cross section of the dam gets fully saturated and leaking water appears on the defended side and the whole dam is soaking wet.

The analytical and numerical methods for dam leakage determination

Analytical calculation methods

Leakage determination along the dams, flood protection dams and other man-made objects is very important. If there is a doubt about the durability of a dam in terms of natural causes or risks, it is a vital question. To determine and measure leakage there are several ways but there is no absolutely perfect solution to these hydraulic problems.

During the investigations we examined the leakage of dams and subsoil separately, the way as if the bottom of the flood protection dam was made up of watertight rock. We assumed the body of the flood defence as homogenous and the following analytical methods were used to compare the results of the following simulations.

- the Casagrande method [9];
- a modified Casagrande-Kozeny approach [10];
- and the Pavlovszky method [11].

We also compared the obtained results of these analytical methods with the numerical ones of the GMS SEEP2D module.

Numeric method: The Groundwater Modeling System (GMS) program package

The SEEP2D module of the Groundwater Modeling System (GMS) package can be used effectively to clarify 2 dimensional unconfined and confined leakage problems [12]. The SEEP2D module of the GMS program package uses two-dimensional triangular shaped finite units. The shape and the size of a single unit can be optional even within the same system. Of course the increase of the number of units can yield increased computational time.

In the SEEP2D module, there are two possibilities to solve unconfined leakage problems. One possibility is when the solution is calculated only for the saturated zone and the modeled area is distorted up to the highest point of the leakage area. The calculated result is then made up of a geometrical and a solution file. In the second case the net is not deformed and besides the flow, the net of the saturated and the non-saturated zone can be modeled.

With the help of the SEEP2D module all kinds of data of any dam of inner-structure can be obtained. The problems investigated by us cover only open, unconfined, steady-sate systems.

The investigation of the dam at Lázbérc reservoir and three flood dams along the Tisa and Bodrog river using SEEP2 module

The first step in our work was to import the geometrical features of the dams into the program. Then we focused our efforts on making the structural flood defence and modeling.

As a next step, our intention is to present the results obtained from using the SEEP2D module of the GMS modeling package. We examined the dam of Lázbérc reservoir (stores surface water for drinking purposes) at a certain water level (maximum operating water level) because this state can be considered stationary. In the case of flood defence dams along the Tisa river we prepared our models for a higher water level and a lower water level because we cannot talk about steady state conditions in time - although this state could be observed during the slow recess of water after the 2006 floods. So steady-state approaches were applied for the different water level simulations.

Case-study investigation from the Lázbérc reservoir

The actual hydrodynamic data of the reservoir at Lázbérc - for example the hydraulic conductivity values – were not available during the investigation because real information for the dam itself are not present in the waterworks database. All they could provide us was the information that the material (clay) used for the building of the dam was transported from the clay mine from the north direction of the reservoir. Although our investigation serves many purposes, we were not able to calibrate our simulations because of the shortage of real measured conductivity data.

However, there are vertical leakage units installed every 15 meter under the dry edge of the dam, which are one meter in width and are connected by a drainage system towards the dry edge of the dam. So there are manholes for observations of the water leakage discharge coming from different sectors of the drainage system, which are connected by drain pipes (Fig. 2) [13].

Fig. 2. Drain pipes in the left and right.

The volume of the leaking water is measured in cubic meters/days five times a month (on the 1th, 7th, 14th, 21th and 28th of every month) (Fig. 3).

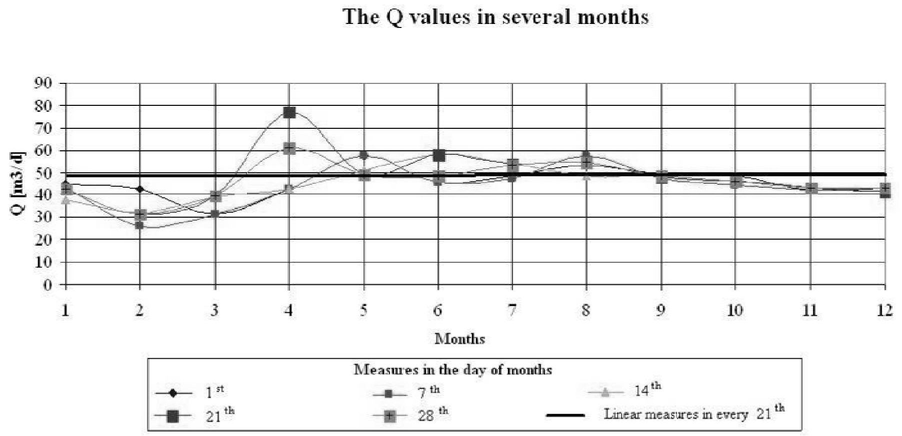

Fig. 3. Count of the leakage measurements along 4 months.

By knowing the volume of the leaking water through the dam we can determine the value of the '***k***' permeability parameter. As a fisrt step, we applied three assumed permeability factors which are typical of clay (Tab. 1). We started with the smallest hydraulic conductivity. Based on this value, we got a q (specific yield) value then by multiplying it with the whole length of the dam (250 meters), we determined the $\boldsymbol{Q}$ (yield for a day). We compared it (Fig. 3.) to a given trendline (the value of this - Q_h=49.89 m^3/d) of the real system.

Based on the obtained result, it was concluded that the value we had used is lower than the volume of leakage measured on site. As a result of this, it seemed necessary to choose a higher value for hydraulic conductivity.

Tab. 1. The assumed hydraulic conductivity 'k' values.

Material's name	***k*** [m/d]
core$_{(1)}$	0.000086
core$_{(2)}$	0.00864
core$_{(3)}$	0.00764
drain	20

As a next step, we chose a new hydraulic conductivity value to be two order bigger than the previous one (Tab. 1). Then we determined the value of Q as it was mentioned above (Q=56.42 m^3/d). In this case wegot a higher value compared to the trendline so in the end we registered a middle value for k. This value represented the real conditions most so we are going to deal with this case in the following.

To avoid any listing of unnecessary data, we are not going to detail how the calculations were made. In the following tables the details of the registered and calculated figures are summarized.

Tab. 1. The counts of relative yield 'q', yield 'Q' and exit length 'a'.

	Q [m^3/(m·d)]	***Q*** [m^3/d]	***a*** [m]
1. case	0.0023	0.575	21.94
2. case	0.2257	56.425	21.94
3. case	0.1996	49.9	21

Calculation details of flood protection embankments/ dams along the Tisa and Bodrog rivers

Based on the data received from the Department of Flood Protection and Water Regulation of the Northern-Hungarian Nature Conservation and Water Inspectorate, three typical structural embankments/dams (two of them were the right side of the River Tisa, one of them was the left side of the River Bodrog) were investigated. The basic data concerning the dams are summarized in Tab. 3. Knowing the geometrical data of the dams, first the dams were put into the system. The outlined cross-sectional area clearly showed the state of the embankment/ flood protection dam before the developments and after the developments (Figs. 10 and 11).

The Water Inspectorate planned to start the static examination of the embankments/dams based on experience of former flood data in 2000. Construction plans made for this project were ready in 2003 [14].

To calculate and to set up computer modeling we used their data.

Tab. 2. Basic data of the dam [15].

Geometrical properties of the dams

Description	**Sign**	**Unit**	**Value in the cross section** (river [km])		
			Tisa right side 48+400 (Cigánd)	**Tisa right side 27+351** (Révleányvár)	**Bodrog left side 28+750** (Halászhomok)
Height of bank	H	m	5.5	4.9	4.5
Base width of bank	B	m	50.3	39.1	30.4
Width of dam crest	b_k	m	6.5	4	4
Bank slope of water-side	ρ_v		1\3	1\3	1\3,5
Bank slope of save-sides	ρ_m		1\4	1\3	1\3,7

Properties of subsurface medium

Depth of permeable layer	d_0	m	1	2	2
Permeability of permeable layer	k_0	m/d	0.43	0.034	0.086
Depth of upper layer	d_f	m	2,3	–	3.,8
Permeability of upper layer	k_f	m/d	0.000086	–	0.000086
Angle of internal friction of subsurface	φ_a	°	18	18	12
Cohesion of subsurface	c_a	kN/m^2	8	10	40
Angle of internal friction of bank	φ_t	°	20	16	16
Cohesion of bank	c_t	kN/m^2	20	40	40
Density of bank (telített)	φ_t	kN/m^3	20	20	19.5

Results of analytical calculations

The most important methods of analytical calculations concerning leakage through flood protection dams were reviewed and examined in this section.

It is worth starting with the evaluation of application possibilities if we want to compare the different methods.

The easiest way for calculation is the modified Casagrande-Kozeny method. A bit more difficult calculation approach is the Casagrande method. The most complicated one is the Pavlovszkij method, even if we used the well-known simplified approach [16].

The Casagrande method and the modified Casagrande-Kozeny method gave nearly the same relative yield value (q) while the Pavlovszkij method showed some differences compared to the previous ones. Fig. 4 shows the results of the relative yield value of leakage leaking through the dam of Lázbérc Reservoir based on using different methods of calculations.

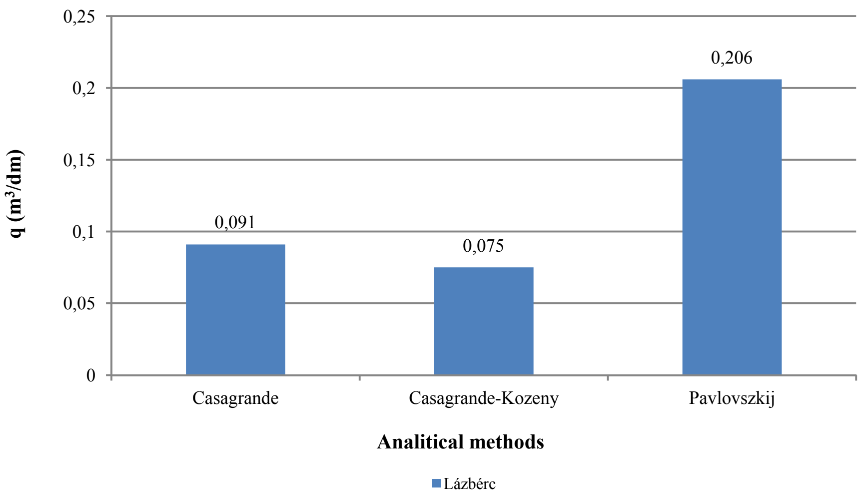

Fig. 4. The comparison of the 3 analytical methods to estimate the leakage.

Looking at the results it is clear that the different methods of calculations resulted in a little bit different values. Fig. 5 shows the obtained results of calculations concerning different river embankments/ flood protection dams.

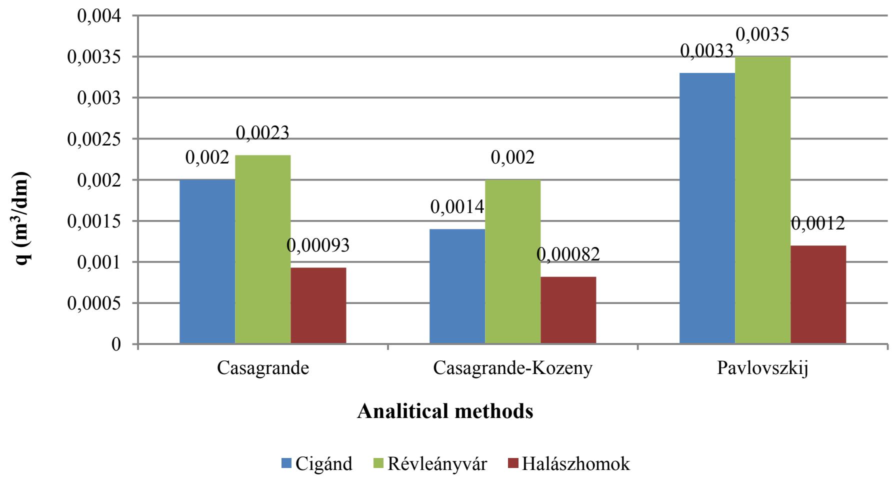

Fig. 5. The relative yield 'q' values for the different dams using analytical approaches.

In our opinion, these differences can be explained by the differences in the applied hydraulic approximations.

On the protected side, based on the results of the length (*a*) of the free leakage surface (Fig. 6.) it can clearly be seen that the highest values were obtained by using the Cassagrande method, and by using the other two method we obtained lower values.

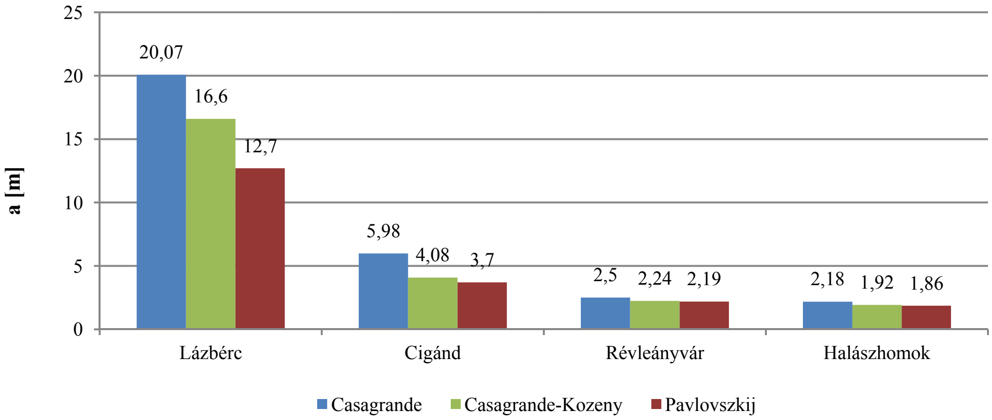

Fig. 6. Changing the length of exit with the 3 analytical method.

The obtained results show how analytical solutions can differ. The Casagrande method and the modified Casagrande-Kozany method show similarities. In the case of more complicated and more complex flood protection dams, analytical solutions are neglected because they are incapable of exact description of leakage.

Results of the numerical solutions

Modeling results obtained from SEEP2D module

As a next step, we applied the SEEP2D module of the GMS 6 program for modeling activity. First we recorded the coordinate values concerning the geometrics of the dam. Then we did the division of the geometrics. Then the program generated a finite grid net (Fig. 7).

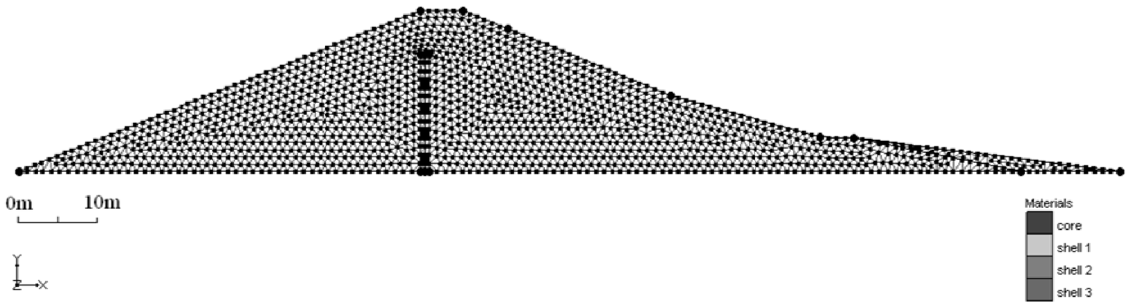

Fig. 7. The finite grid net of dam at Lázbérc.

The next step involved feeding material characteristics into the SEEP2D module. The above-mentioned leakage factor values were taken into consideration in the program. Based on this information, the SEEP2D module is able to determine the shape of the leakage area, the equipotential lines as well as the ***q*** relative yield (Fig. 8 below).

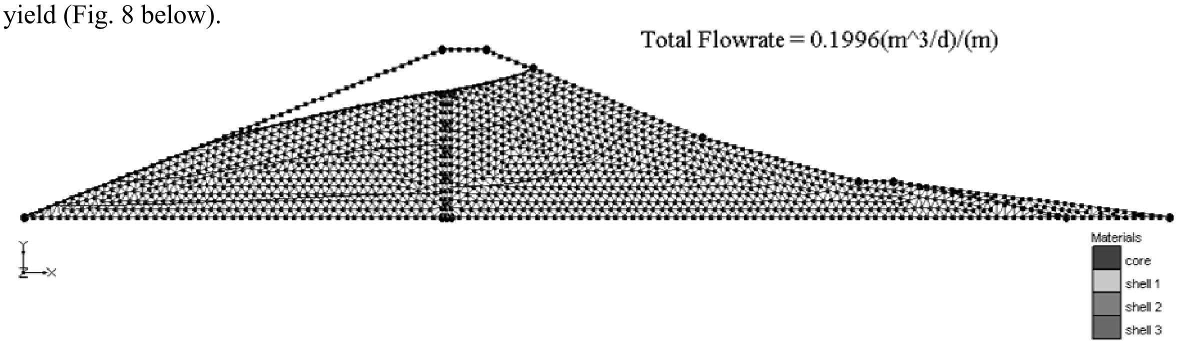

Fig. 8. The leakage and equipotential lines in dam.

In the following the hydrodynamic pressure behavior was also investigated. Fig. 9 illustrates the changing values of water pressure inside the dam. It can be seen clearly, that the values of water pressure are the highest on the side of storage space.

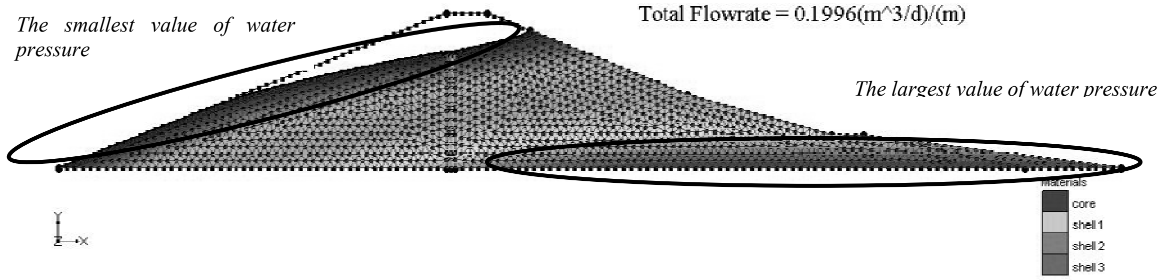

Fig. 9. Pressure values in dams.

The results obtained during the modeling of flood protection dams are shown in the following summary.

Summary of the modeling results

During the modeling phase the hydraulic characteristics of the Lázbérc reservoir and three separate river flood protection embankments were investigated. We examined a complex water storage system at the Lázbérc dam while in the case of the flood protection embankments we carried out our simulations at a lower water level first, then at a higher (flooding) water level. The characteristic values of dams as well as modeling were calculated by using the Groundwater Modeling System program with the SEEP2D module.

Based on the result of the modeling simulations, the following conclusions can be drawn:

1. First we examined the Lázbérc dam. In this case - as there were no available hydrodynamic data at hand – we had to generate the '*k*' conductivity or permeability values for ourselves, so the figures were not accurate but very close to real figures (trial-and-error approach). Using the program, we determined the average permeability for the material of the dam, and we presented it to the ÉRV Water Management and Waterworks Company. (k=0.00764 m^3/d). Moreover leakage or flow, pressure (head) and speed conditions were also examined inside the dam (Figs. 8 and 9).
2. It is understood that an extensive fall of the water level inside the dam is according to observed reality (Fig. 9.). It is further underlined by the fact that speed in the leakage increased. The pressure value has reached its peak on the right side of the dam where the water pressure is highest, because it is on the side of the reservoir.
3. The next investigation covered three typical flood protection embankments in the area of the Department of Flood Protection and Water Regulation of the Northern-Hungarian Nature Conservation and Water Inspectorate, which are considered to be typical in the region. In the case of the modeled lower water level or higher water level, only the difference of the scale of the relative yield can be observed while the nature of leakage, pressure and speed values remained the same. (Figs. 10 and 11). This similarity is due to the fact that in all the three modeled cases only the water levels were different.

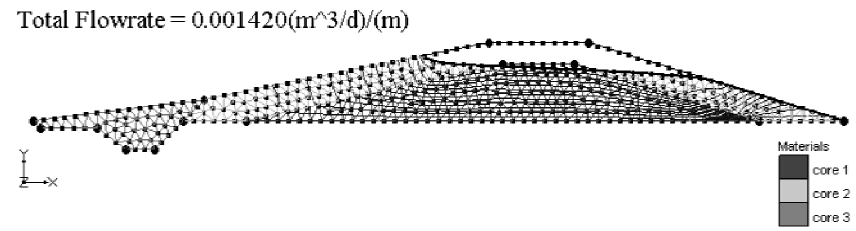

Fig. 2. The leakage and equipotential lines in the dam at Révleányvár.

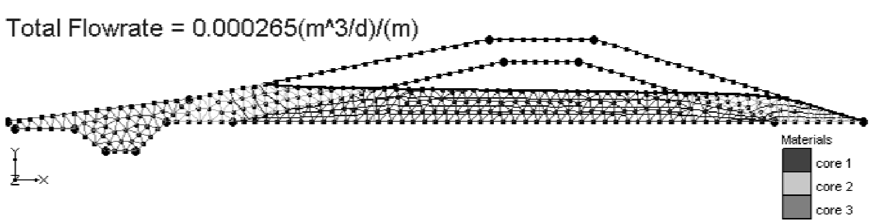

Fig. 3. Leakage in the dam in case of a lower flood level (Révleányvár).

1. Deductions could be made during the analysis of the outgoing coordinates. In all three cases water comes out of the dam on the protected side at a higher point when the water level is high and it comes out of the dam on the protected side at a lower point when the water level is low (Tab. 4).

Tab. 3. Coordinates of the exit points in the saves side.

Size	x coordinate [m]	y coordinate [m]	a [m]
Large flood level	36.3	2.27	3.76
Small flood level	38.1	0.6	1.34

2. Concerning the parameters of the modeled dams in the region of Cigánd and Révleányvár, there was very small difference between them, or there was not any difference at all. In our opinion it was due tothe fact that there are significant similarities in the geometrics, the inner structure, leakage factors of the dams.
3. The third modeled case significantly differs from the ones examined before. (Fig. 12). It is understood that this difference is the result of the different structure of the dam

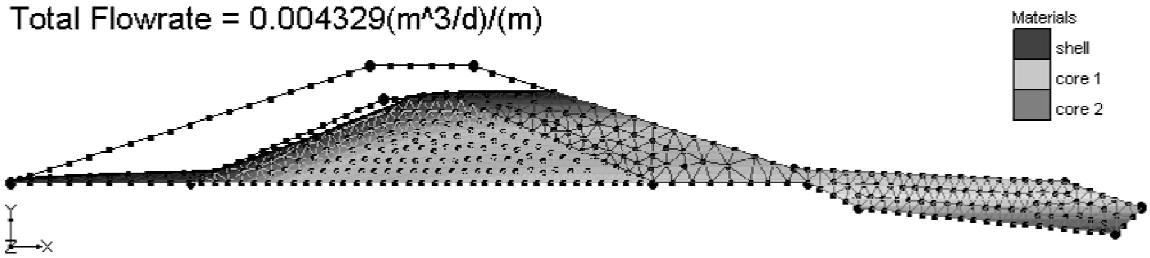

Fig. 4. Distribution of pressure on Halászhomok dam with the method of modeling.

Comparison and summary of the analytical and numerical results

So far we have reviewed and examined the different significant analytical methods of calculations of leakage through dams. Then we made computer models of the hydraulic characteristics of dams using finite element approach.

The relative yield value of the cross section of Lázbérc dam is shown in Fig. 14. The horizontal line shows the different methods of calculations, the vertical axis shows the q relative yield obtained during a given application.

The following statement can be made based on Fig. 13:

- The Casagrande and the Casagrande-Kozeny analytical methods showed great similarities.
- The results of the Pavlovszkij and the GMS 6 methods significantly differ from the Casagrande and the Casagrande-Kozeny methods.
- The results obtained from the latter two calculations are nearly the same. This is very interesting because as we detailed above the GMS-6 programme calculates figures very close to reality. So we can say that the Pavlovszkij method is the most important of the analytical calculations in the case of the Lázbérc reservoir.

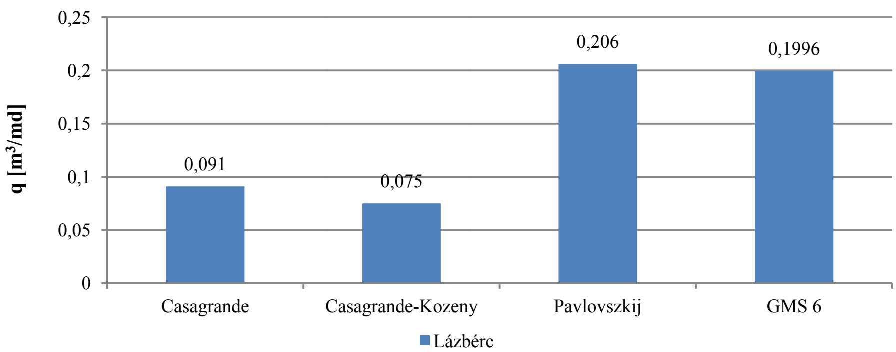

Fig. 5. Relative yield values in dam of Lázbérc using the different methods.

- The Fig. 14 describes yields that leak through the whole length of the dam where the horizontal axis shows the types of methods. The Q value in the chart was obtained from multiplication of the q relative yield and the length of the dam (250) meters so the above mentioned statements can be applied here as well.

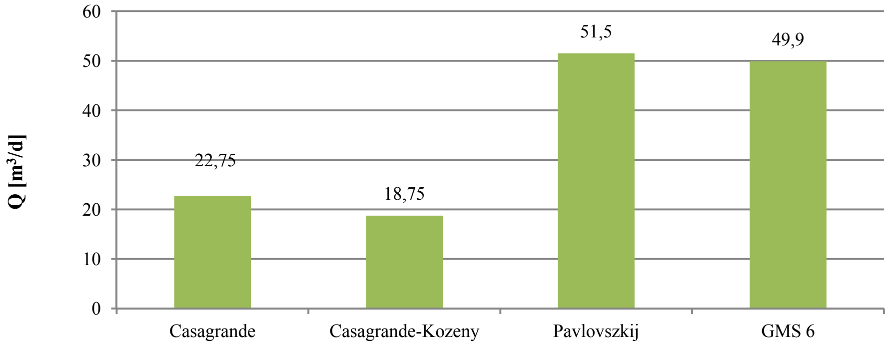

Fig. 14. Amount of leaked water along the full dam using all methods.

In the following we compared the results of the investigation of three typical sections of flood protection dams. In the chart below similarly to the charts above the vertical axis and the horizontal axis shows the yield and the given method. Here the obtained results were different from the ones of the Lázbérc reservoir:

- In this case the GMS 6.0 - which is the most significant and realistic program - gave the most useful data. It is because the variation in the internal structure of the dams can be characterized with the help of this program package.

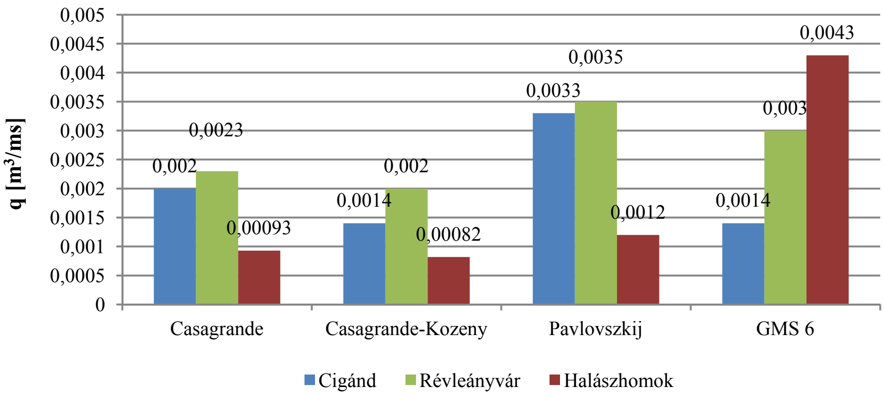

Fig. 15. Relative yield values.

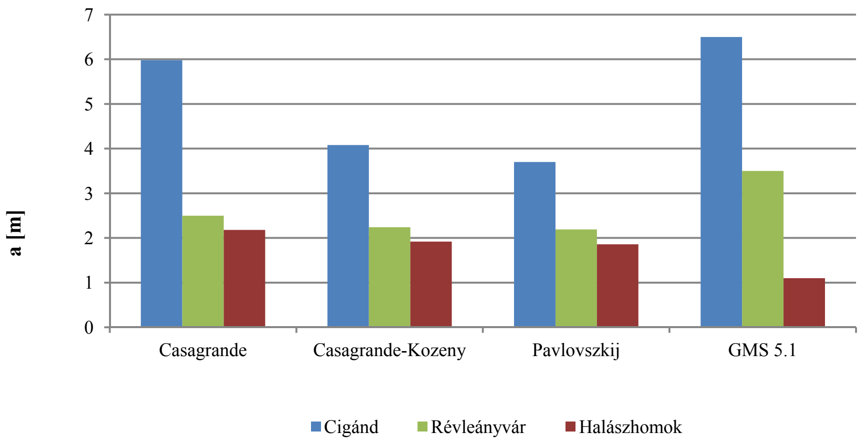

Fig. 6. Length of exit in the saved side.

- Contrary to the previous case (Lázbérc) the Pavlovszkij method doesn't show obvious similarities with the data obtained from computer simulations. The only exception is the case of Révleányvár where the results are greatly compatible with the the case at Lázbérc.
- During the investigation of the section of the dam at Cigánd there is an interesting difference contrary to the previous ones - the data received from the GMS 6 programme showed similarities with the data received from the other two (Casagrande, Casagrande¬Kozeny) analytical methods.
- During the calculations at Halászhomok, the results of the three analytical examination completely differ from the ones received from the numerical simulations. The simple explanation may be that analytical methods cannot take into consideration the variation of the leakage factor.

Finally, we summarized the length of water leaking at the protected side of the dams. (Fig. 16) There were similar differences shown here because of the above-mentioned reasons (internal structure) as we have seen in the investigated cases before.

To draw a conclusion, we can determine that the computer program used during the trials was a great help to experts, since in the case of dams with inhomogenous structure or internal structure analytical solutions are left behind because of the complicated and awkward calculations and because they cannot describe leakage with appropriate certainty. In these cases when there is a need for safe technical characteristic the above mentioned computer modeling is indispensible.

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