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Hydrodynamic and slope stability modelling of flood protection embankments and valley dams

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Hydrology conditions in recent years clearly demonstrate that flood protection is a priority task for Hungarian water management, and its importance cannot be questioned. This study examines three flood control embankments and two dams, including their subsoil characteristics. The examinations also contain the modelling of slope stability and seepage conditions. The seepage models were created with the Groundwater Modeling System 10 SEEP2D module, which uses the finite element method. As a part of the examination of the seepage models, we examine the free flows and the embankments' seepage conditions. Changing the modelling parameters also affects seepage conditions. Thus we examine the effects of the embankment's foot width and on the total flowrate and the seepage conditions. Our examination also includes a study about the effects of neglecting the subsoil in computations. For the slope stability examinations, both the Groundwater Modeling System UTEXAS module and the Soilvision SVSlope module are used, and their results are compared, showing significant differences. While the slope stability measurements were done in a dry state, we also examined the effects of pore water pressure on the embankments' stability. Modelling methods are useful and simple methods for the examination of seepage and slope stability of flood control embankments and can provide great help to flood protection professionals.

Key words*: flood protection, slope stability, finite element modelling, dam seepage*

Introduction

Flood protection and drinking water supply are among the most urgent tasks of water management in Hungary (Ilyés et al., 2017; Palcsu et al., 2017). According to extreme weather conditions, floods along rivers or flash floods mean real risks to the civil society and to nature, not only in Hungary but all over the world (Francois et al., 2019). This is the reason why the proper operation of embankments is vital to have successful flood control. It is important to know how an embankment is behaving during a flood period. What kind of processing exists inside the embankments concerning water level and stability issues? To understand these physical processes, simulations methods can be used successfully in flood control processes (Xiaohui, 2017).

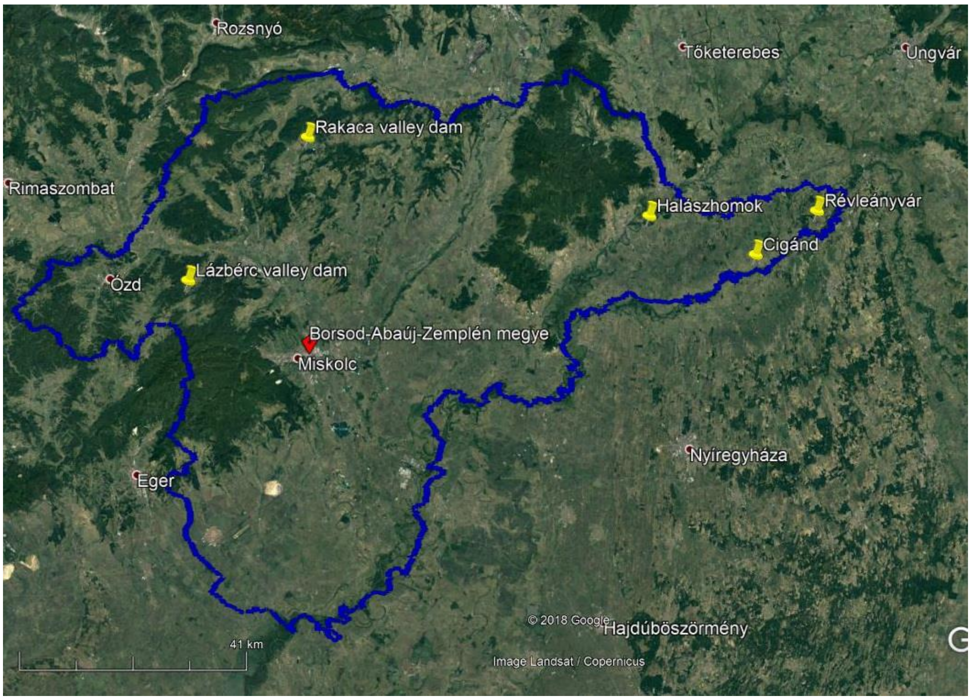

Fig. 1: Location of the examined structures, Borsod-Abaúj-Zemplén county.

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Along the Tisza river in Hungary, the flood protection is mostly executed with the help of embankments. The increasing agricultural and settlement land use during the centuries made it necessary to develop a protection line covering the whole section of the Tisza river (Vágás, 2007). More precise knowledge of the related hydraulic relations of these protection lines is increasingly needed because huge damage can occur if the protection lines are destroyed. The purpose of valley dams is to control the even or changing runoff of the watercourse based on the needs of the users (Sternberg, 2006). They typically contain a structural element to control water leakage; thus, it is essential to be aware of these leakage conditions. In this study, we examined the seepage conditions of three flood protection embankments and two valley dams. These structures are situated in the north-east part of Hungary, in Borsod-Abaúj-Zemplén county (Figure 1). This work extends previous studies (Zákányi and SzŤcs, 2010, 2013) by taking subsoil into consideration. The obtained results can be generalized because simulation methods are very important in proper embankment design.

Flood protection in Hungary

In the Middle Ages, floods did not have a high damage factor. The environment of the rivers shows its natural status: wide floodplains, huge woody areas that decreased the flood water level. The improvement of agriculture brought the necessity for river regulation and floodplain draining. At the time of the regulation of the Tisza River, safety was secured by the height of the embankments practically by the end of the 19th century. The embankmentôs prescribed height was regulated to the largest formerly experienced flood with the addition of safety height (Nagy, 2014). However, the highest water level of rivers started to increase with the regulation of rivers, the development of the infrastructure and the growth of the agricultural lands (Vágási, 2007). Based on the eraôs protection philosophy, so-called bulbous structured embankments were made with the construction in several cycles (Figure 2). Nowadays, the length of the Hungarian flood protection embankments is more than 4,200 km (Nagy, 2003).

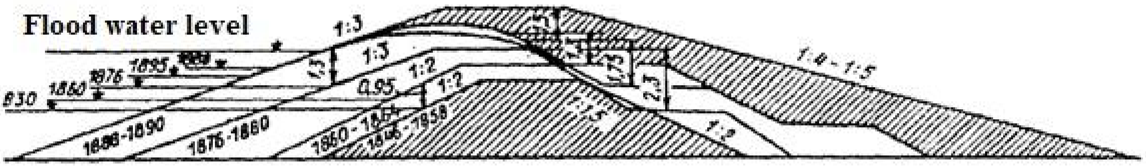

Fig. 2: The increase in the height of the Széchenyi Dam between Tiszadob and Polgár, 1845-1890 (Mihalik, 2000)

Besides the construction of embankments, we have to deal with another problem as well. The embankments are often built on unsuitable subsoil that contains permeable layers. The presence of these permeable layers increases the probability of the formation of sand boils (Nagy, 2008). The key element of flood protection is the stability of the flood protection dam. The failure and ruin of the embankment carry the possibility of catastrophe (Kádár and Nagy, 2017). Hungaryôs reservoirs, in addition to water supply, also provides flood protection because they delay the runoff of harmful excess water. The inland reservoirs are mostly bordered by valley dams, whose embankment was built from clay, which, in most cases, we cannot consider as an aquiclude. Therefore, the leakage through the dam has to be controlled, and leaking water has to be removed out from the embankment. The task of the interception drain is to block the dangerous seepage process and to decrease the dangerous pressure conditions in the embankment. Its material is mostly coarse-grained sand and sandy gravel. The advantage of its use is that it collects the leaking water in the water-side dam body and removes it from the dam, thus blocking the wetting of the dam across its whole cross-section. Nowadays, another problem for flood protection and drinking water reservoirs is extreme weather conditions. As we experienced in 2010, extreme floods formed in the Sajó and Bódva Rivers, and also in the Tisza River in the early 2000s (ZeleŔákova et al., 2018).

Site description and methodology

In Hungary, the valley of Tisza river is affected by floods mostly. During the 20th century, and after the 2000s, many floods were formed, and it caused several problems in flood protection, and the stability of the embankments. Considering this situation, we decided to deal with this area, especially the upper part of the Tisza river. During our investigation, we used the hydrodynamic and slope stability modelling, which is an important tool to know the hydraulic behaviour and its effects on slope stability. With the help of this tool, we can conclude the most frequent failures (hydraulic failure, seepage failure, piping) near the embankments, and dams (Shivakumar et al., 2015). We modelled three flood protection embankments near the Tisza River (near Cigánd, Révleányvár, and Halászhomok) and two valley dams (Lázbérc and Rakaca) during our investigation.

For the leaking model, the program applied was the SEEP2D module of Groundwater Modeling System 10.0, and for the examination of slope stability, the module of Groundwater Modeling System 10.0 UTEXAS and the module of Soilvision Slope were used. The Groundwater Modeling System (GMS) is a comprehensive graphical user environment for performing groundwater simulations. The entire GMS system consists of a graphical user interface (the GMS program) and a number of analysis codes (MODFLOW, MT3DMS, SEEP2D, etc.) (Aquaveo, 2019).

All of the programs apply the finite element method as the numerical method. The word ónumericalô stands, in this case, for approaching a solution (Völgyesi 2008). Numerical solutions approach the real situations in a way that they make sections of ongoing procedures in time and place (Kovács, 2004). In the finite element method, as opposed to the finite difference method, the given geometry can be precisely covered with arbitrarily shaped elements. Thus, the elements orient much better to the real range than when applying a different finite mesh (Durbin and Bond 1998; Zákányi and SzĬcs, 2010). The orientation of the elements to the original geometry helps to make the model accurate and to determine water flowing across the embankment more accurately.

SEEP2D is a two-dimensional steady-state finite element groundwater model, which is widely used in such calculations. Both saturated and unsaturated flow is simulated. SEEP2D is designed to be used on profile models (XZ models) such as cross-sections of earth dams or embankments. With the help of the SEEP2D module, we calculated the total flow rate, which is the flow rate into (out of) the problem domain (Aquaveo, 2019).

UTEXAS is a slope stability software package created by Dr Stephen G. Wright of the University of Texas at Austin. UTEXAS is used to analyze slope stability using the limit equilibrium method. The user provides the geometry and shear strength parameters for the slope in question and UTEXAS4 computes a factor of safety against slope failure. The factor of safety for a candidate failure surface is computed as the forces driving failure along the surface divided by the shear resistance of the soils along the surface. UTEXAS4 is a state-of-the-art slope stability code and has been widely used in industry for many years (Wright, 1999).

The hydrodynamical models show "steady state" at the same time because the SEEP2D module cannot handle the transient state. In the case of the valley dams, the water level of the reservoir has relatively small-scale fluctuation. Thus, the "steady-state" is presumed. And in the case of flood protection embankments, we can calculate with a permanently high flood level.

For the slope stability investigation, we used the Slope module of SoilVision software, which also calculate with the limit equilibrium method, and it also can calculate with the effect of leaking water.

Material characteristics of valley dams and flood protection embankments

We had to give several parameters during the examination of flood protection embankments and valley dams: for the leaking model, the parameters given were horizontal and vertical factors, for the modelling of slope stability they were cohesion and internal friction angle. Furthermore, effective porosity was necessary for the definition of given parameters. Some of the applied parameters were provided by the regional waterworks company, called ÉRV Zrt., while the rest were taken from a previous study (Zákányi and SzĬcs, 2013). The related data (not publicly available) of the geometry of the examined embankments was provided by ÉRV Zrt. and ÉVIZIG (the Water Management Directorate of Northern Hungary).

During the modelling, not all of the parameters requested by the program were available; unfortunately, sampling and lab examinations are possible only with the proper permission, and in the case of embankments only allowed in a justified case. For these reasons, we had to find data from another source. We used a Hungarian technical guideline (MI 10 269-1982) that contains parameter intervals, from which we chose a value to use in the computations.

In this paper, the construction and material characteristics of embankments are introduced based on the embankment of Cigánd. The shape of the embankments clearly shows the bulbous structure. Considering the subsoil, we can divide it into a permeable layer and a cover layer. The embankment was built with these two characteristic layers, in which a core and a surrounding shell can be found (Figure 3, Tables 1 and 2). The geometry of the dyke at the riverside was recorded by the information offered by ÉVIZIG (Zákányi and SzĬcs, 2013).

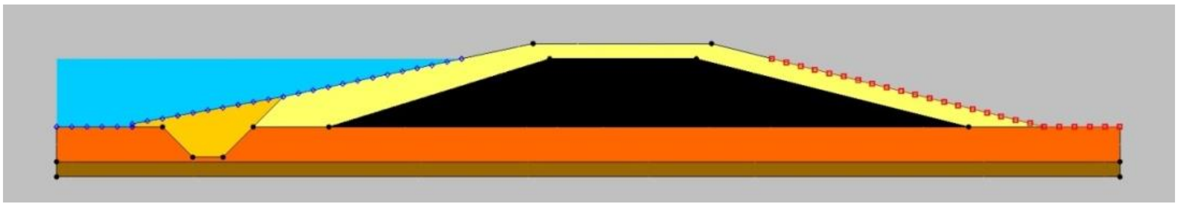

Fig. 3: Cross-section of the flood embankment around Cigánd

Table 1: Hydraulic conductivity values of the embankment of Cigánd

	k_h (horizontal) [m/d]	k_v (vertical) [m/d]
Inner core	0.00864	0.06
Shell	0.000864	0.000864
Impermeable foot	0.000432	0.000432
Cover layer	0.00086	0.00086
Water-bearing layer	0.43	0.43

Table 2: Shear strength parameters of the embankment of Cigánd

	Unit weight [kg/m^3]	Cohesion [kPa]	Friction angle [°]	Effective porosity [%]
Inner core	2100	35	15	35
Shell	2200	40	15	30
Impermeable foot	2200	40	15	30
Cover layer	2200	40	15	30
Water-bearing layer	2000	0	29	40

The conformation of the valley dam will be demonstrated in this paper by the reservoir dam of Lázbérc (Figure 4). The two dams investigated here are different in that an impermeable wall was not constructed under the Rakaca reservoir dam. The seepage parameters are shown in Tables 3 and 4. For the parameters of shear strength for the Lázbérc valley dam, in case of the watertight wall and bedrock, we assumed non-porous, grainy rock. When the ñhard rockò option is chosen among the types of material, the program does not ask for the cohesion, internal friction angle, or effective porosity. The bedrock is limestone, and the impermeable wall is concrete; thus, these parameters were not necessary for the program.

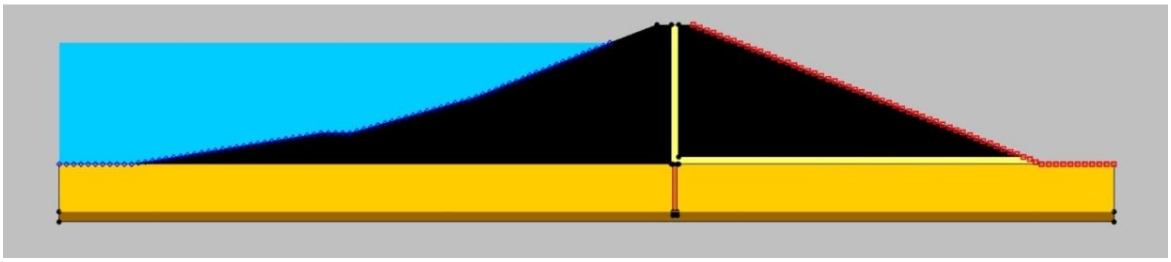

Fig. 4: The cross-section of the valley dam of Lázbérc

Table 3: Hydraulic conductivity values of the valley dam of Lázbérc

	Dam body	Drain	Subsoil	Watertight wall	Base rock
k [m/d]	0.00864	8.64	0.043	0.0000864	0.000864

Table 4: Shear strength parameters of the valley dam of Lázbérc

	Unit weight[kg/m^3]	Cohesion [kPa]	Friction angle [°]	Effective porosity [%]
Dam body	2000	40	15	30
Drain	2000	0	30	32
Subsoil	1800	10	25	25
Watertight wall	2500			
Base rock	2200			

Calculation results of hydrodynamic, and slope stability simulations

During the modelling, our examination covered leakage models and slope stability problems. The hydraulic modelling of the dam and its subsoil can be easily implemented with the help of GMS 10 program, and we have the opportunity to carry out a slope stability examination with the consideration of water seepage. After the water level and exit surface are provided, the program calculates the rate (the blue and red lines, respectively, in Figures 2ï 7), the rate of the flow velocity inside the dam and the pore water pressure and total flow rate, from which diagrams of the calculated rates can be easily made for visualisation. During the determination of the total flow rate, the program calculated the flow rate related to a one-meter-long part of the embankment. For each embankment, we took the standard flood level as the basis, which is located one meter downwards from the shoulder, while for the valley dams, we took the maximal operational level into consideration. Using the SoilVision program Slope package and the GMS UTEXAS module, we examined the slope stability; one of the purposes for this was to compare the two programs. With the Slope module, we examined three stages. In one case we did dry condition modelling, in the other case we put the rate of pore water pressure calculated by the GMS as a discrete point into the Slope module and thus we took the water pressure into consideration. To consider the effect of water, we recorded the highest flow line calculated by the GMS in the Slope module and set it as water level. We compare the results of the different cases.

The GMS UTEXASô module considers the flow relation and the rate of water pressure calculated by the SEEP2D module, and thus calculates the critical slope failure surface with the Spencer method and its belonging security factor. All slope stability tests were done by the method of slices, followed by several types of calculation methods. The security factor and the place of critical slope failure surface were calculated by the Bishop, Spencer, Janbu and Morgenstern-Price methods, which all assume round slope failure surface.

Seepage conditions

Our aim during the application of GMS SEEP2D was the examination of the ongoing leak process of different geometrical and structural embankments. For the demonstration of flow conditions, the mesh of models are recorded with one-meter spacing, and on the riverside and protected side, the original ground level runs for a 10-meter-long stretch. The program defines the streamlines and calculates the total flow rate, velocity conditions, and the rates of pore water pressure. The models consider the standard flood water level.

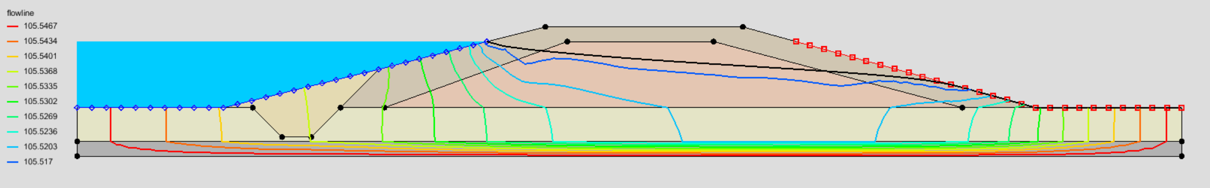

Fig. 5: Flowlines in the embankment around Cigánd

In Figure 5, we can see that the subsoil has an important role in the permeability of embankments because most of the flow lines can be seen in the water-bearing layer. The role of the subsoil can also be examined in the embankment of Révleányvár (Figure 6). We encountered thicker topsoil in the subsoil of the Halászhomok embankment, which prevents the seepage of water into the subsoil. In this case, most of the streamlines ran through the interior of the embankment.

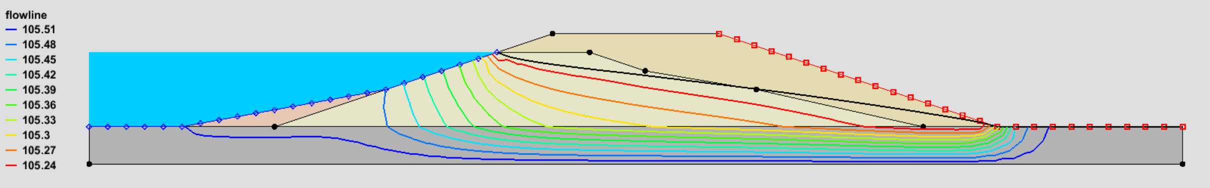

Fig. 6: Flowlines in the embankment around Révleányvár

In the case of the Lázbérc valley dam, the role of the drain inside the dam can be seen during the examination of the streamlines (Figure 7). The water leaking into the dam from the waterside accumulates in the vertical and horizontal sand layer and exits at the foot of the dam. Thus the dam does not get wet throughout its entire cross-section. The concrete wall under the dam blocks the water from leaking through the subsoil. The program allows us to demonstrate the water retention ability of the leaking control elements in dams. The calibration of the model also included on-site measurements from previous examinations. The flow rate of the outflowing water was determined from the collecting tube of the drain system.

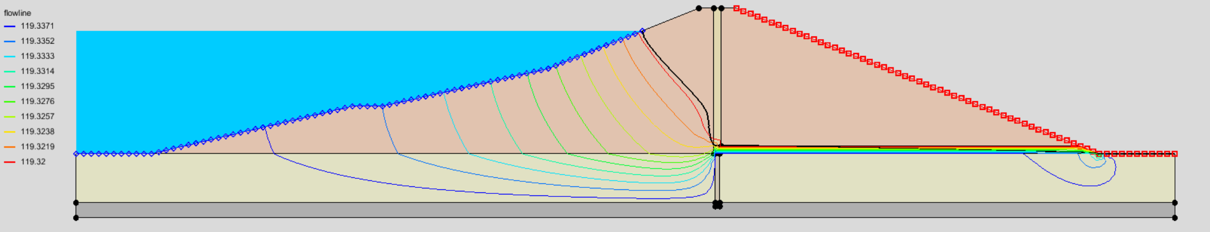

Fig. 7: Structural elements of the valley dam of Lázbérc and the computed streamlines

Looking at the cross-section of the Rakaca dam (Figure 8), we encounter very diverse subsoil. Inside the dam body, we can see that a 1-meter-wide drain system was built. The sandy and rocky drain system consists of a vertical drain, a right-angle bend, and a horizontal section (3% gradient). The water in the drain system is led off to the protected side by a 0.3-meter diameter concrete drain tube (not visible in the figure). The whole leakage system output flows into a container.

Examining the streamlines in Figure 7, it is visible that a layer can be found in the subsoil whose hydraulic conductivity is higher than that of the other materials, and the water flows through this layer towards the protected side. The role of the drain is also important because it collects most of the water flowing through the dam and collectively leads it away from the dam and the subsoil. Because a watertight concrete wall was not built into the subsoil, the streamlines penetrate the subsoil as well (Figure 8).

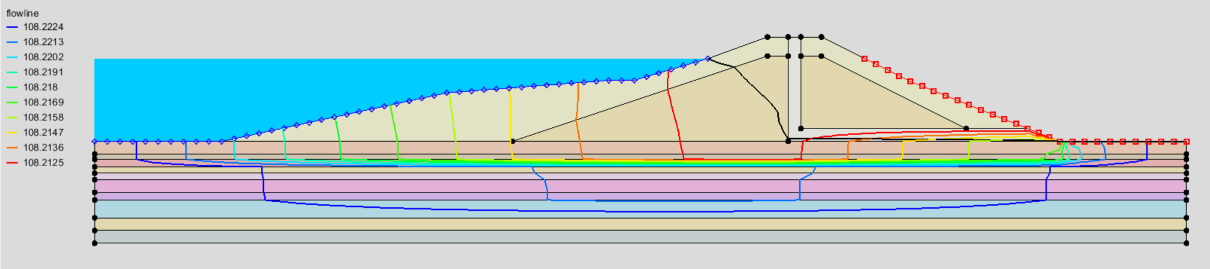

Fig. 8: Structural elements of the valley dam of Rakaca with the computed streamlines

We compared these results with a previous study in which the subsoil conditions were not considered. We made a comparison with the consideration of the total flow rate and outflowing length. From the comparison of total flow rate (Figures 9 and 10), we see that when the subsoil is taken into consideration, higher flow rates are obtained for the flood embankments and in the case of the Rakaca reservoir. The reason for this is that because of the hydraulic conductivity of the water-bearing layer of the subsoil, a high amount of water goes through the subsoil. In the case of the embankments, we have to be aware of the possible formation of sand boils. Because the pressure is high in the subsoil, we have to also count on the growth of pore water pressure, which negatively affects the stability of embankments, because the supporting force against water pressure decreases.

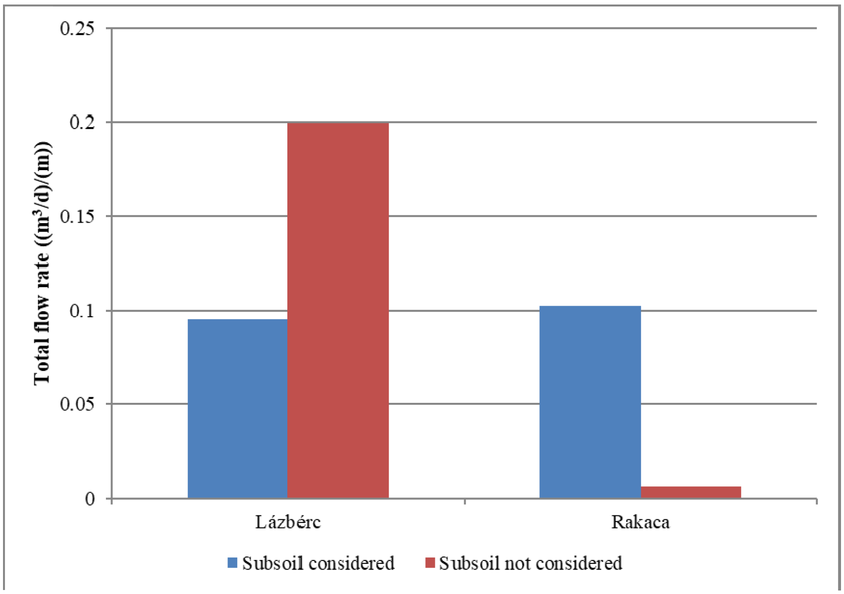

Fig. 9: Comparison of total flow rates for valley dams of two computational models

In the case of Lázbérc, we can see that we obtained a lower total flow rate value when the subsoil was considered. This can be explained by the presence of the watertight concrete wall. The concrete wall stops the water from leaking through the subsoil to the protected side and leads towards the water-bearing sand layer, thus protecting the dam and the subsoil from getting completely wet.

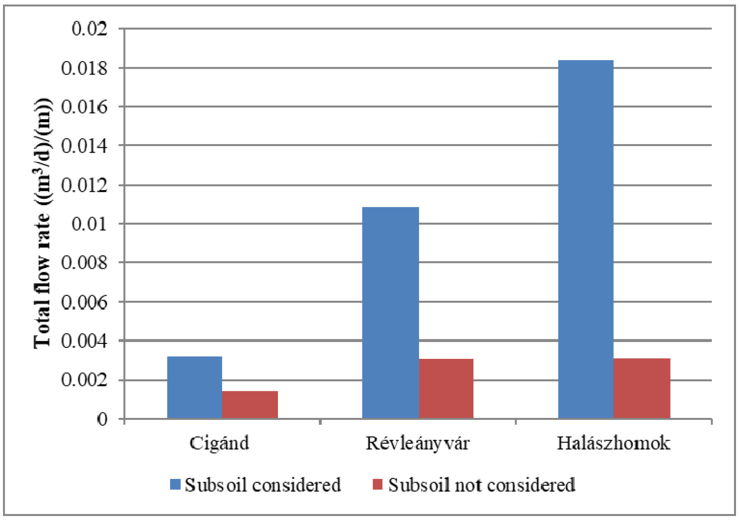

Fig. 10: Comparison of total flow rate for flood protection embankments of the two computational models

The outflow length value offers important information during the examination of embankments. Outflow length means the distance between the highest outflowing point and the foot of the embankment. This rate shows the predicted height of water outflows in the embankments and how wet the embankment has become. We only examined the flood protection embankments for outflow length, because at the dam's reservoir, the water exits through the permeable layers; thus, the outflow length is constant. We calculated the outflow length from the coordinates written by the program and the formula of triangles.

We can see that in case of the flood protection embankments in Révleányvár and Halászhomok, the outflow length occurred at lower levels; however, higher rates were found for the Cigánd embankment. In the Révleányvár and Halászhomok embankments, the subsoil conditions were proper for flow not only through the embankment but also in the subsoil. In the case of Cigánd a relatively watertight layer can be found under the embankment, which did not allow the high degree of infiltration to the subsoil; thus, most of the water flows through the embankment and less goes through the subsoil layer lying under the watertight layer, which has high hydraulic conductivity (Figure 11).

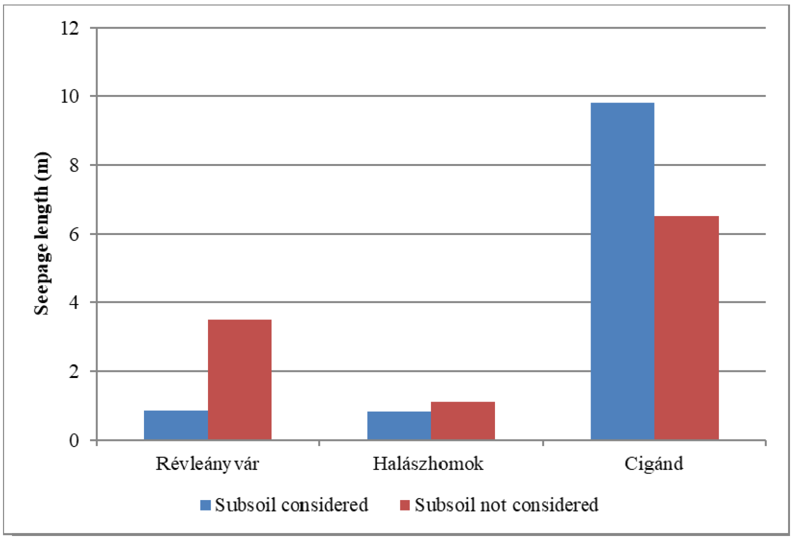

Fig .11: Comparison of seepage length values of the two computational models

Changes in modelling circumstances

During the modelling, we were curious about the effect of two chosen parameters connected to the geometry and mesh. During the modelling, the adoption of geometry was necessary. The aim of the examination was to see how much the width of the embankment foot influences the total flow rate in the model. The width of the embankment foot is defined as the distance between the meeting point of the subsoil and embankment and the edge of the model. Three cases were examined: 5 m, 10 m and 20 m foot width. For the Cigánd and Halászhomok embankments, changing the width of the embankment resulted in the total flow rate increases with the width (Table 6). The degree of the increase in flow rate was not linear. The reason for this is that the exit face grows on the protected side with the foot's width; thus, more water can flow through the system.

Table 5: Change in total flow rate with different values of foot width of the embankment

Foot width of the embankment (m)	Cigánd ($m^3/d/m$)	Révleányvár ($m^3/d/m$)	Halászhomok ($m^3/d/m$)
5	0.0089	0.0107	0.0185
10	0.0113	0.0107	0.0187
20	0.0145	0.0107	0.0191

In the other examination, our aim was to find out how much the choice of mesh density influences the total flow rate and the streamlines. We set the mesh's density in the program by apportioning the embankment's side in a given spacing, and then the program was run based on the mesh. The choice of the spacing is influenced by the size of the given embankment. The differences in spacing between the embankments and valley dams are justified with this.

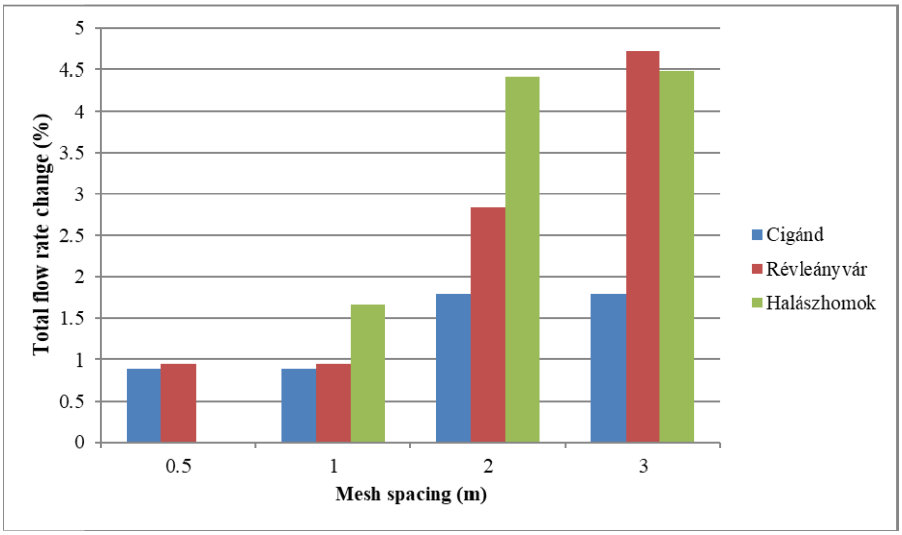

Fig. 12: Total change in flow rate for flood embankments with different mesh spacing

We can see from Figures 12 and 13 that the choice of the mesh's density plays an important role because there can be a 10–12 % difference between the results obtained. Our experience was that the streamlines are influenced by the distribution of the mesh. We observed that the streamlines are shown in much more detail if the allocation of the mesh's division is denser. During modelling, it is necessary to choose the optimum setting, in which the streamlines and the total flow rate both give realistic rates.

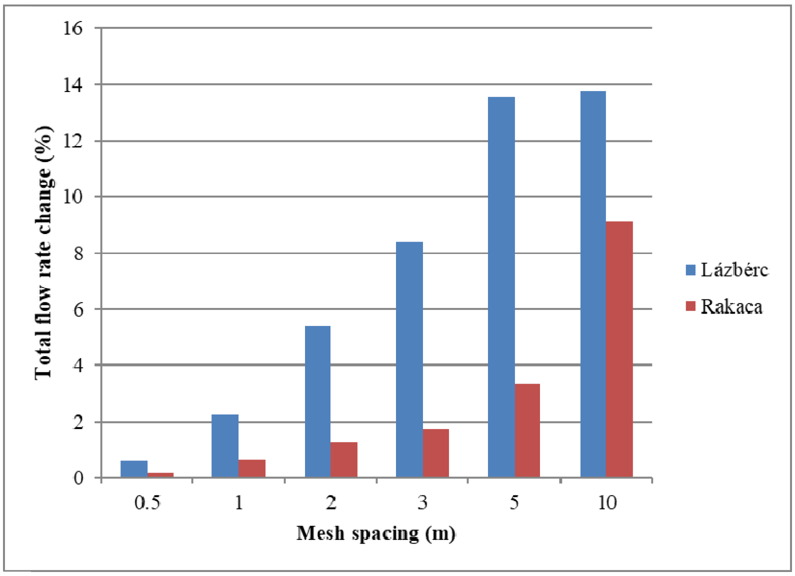

Fig. 13: The total flow rate change at the valley dams

Slope stability modelling

Slope stability examinations were carried out with two programs, the module Slope of SoilVision and with the UTEXAS module of Groundwater Modeling System 10. First, we did the modelling in the dry state with the Slope module. The program calculated the critical slope failure surface and the related safety factors with Bishop, Janbu, Spencer, and Morgenstern-Price methods. Our aim with this examination was to assess the safety of the given geometrical embankments knowing the assumed shear strength parameters.

Naturally, our aim was to define the effect of water on reducing stability using the leakage model. Results of the dry and wet states were compared with each other for all cases and in all slope stability calculation methods. We were also able to compare the two software programs, considering which is easier to use and what kind of differences will be computed by the two programs.

Slope stability without the consideration of pore water pressure

The modelling of dry state was necessary to define the stability reducing the effect of water. In this case, the system has no water in it, and the given parameters are only the volume weight, cohesion and the internal friction angle. The results are shown in Table 7.

Table 6: Factor of safety for dry condition calculated by SoilVision by different methods

	Cigánd	**Révleányvár**	**Halászhomok**	**Lázbérc**	**Rakaca**
Bishop	4.095	2.573	3.746	1.739	2.818
Janbu	3.879	2.482	3.413	1.623	2.666
Spencer	4.104	2.575	3.747	1.756	2.829
Morgenstern-Price	4.113	2.574	3.749	1.759	2.883

Slope stability with the consideration of pore water pressure

We examined the effect of water first with the GMS UTEXAS module (Figure 14). With the UTEXAS module, the program only calculates stability with the Spencer method. The UTEXAS slope stability safety module was provided with the leakage states calculated by the SEEP2D module from a previously given starting circle (the blue circle in Figure 14) using iteration.

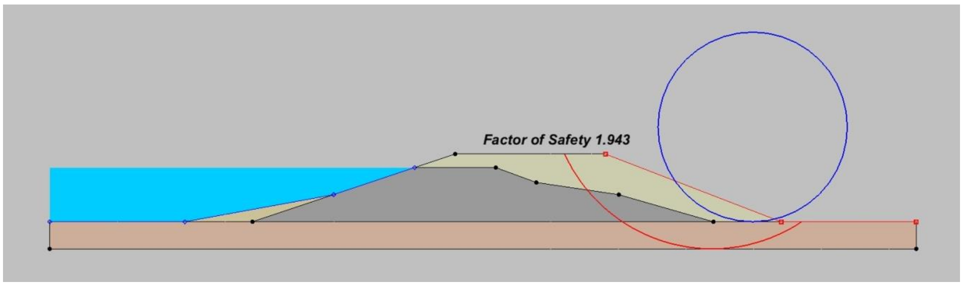

Fig. 14: The embankment around Révleányvár with the critical slip surface and the factor of safety

The effect of pore water pressure can be considered in two ways with the Slope module. One way is to record the pore water pressure rates calculated by the GMS SEEP2D module into the Slope module. These points are intersections of the mesh used by the SEEP2D. The other way is to build the leakage surface calculated by SEEP2D module into the Slope module. We did not give pressure values here, but the highest seepage surface.

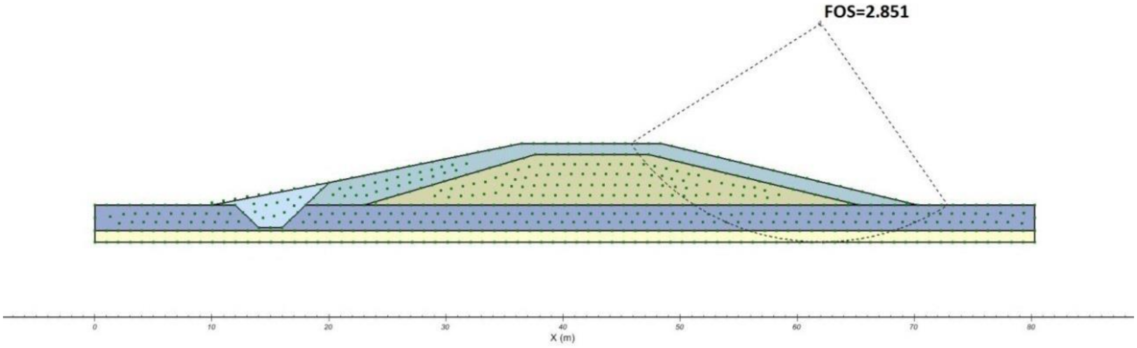

Fig. 15: The critical slip surface and the factor of safety, calculated by the SoilVision Slope module, at the embankment around Cigánd

We simulated the critical slip surfaces (Figure 15.) and compared the obtained safety factors with the safety factors referring to the dry state. The difference between the results for dry state and wet state is given in Tables 8 and 9.

Table 7: Changes in the factor of safety compared to a dry state, considering pore water pressure (discrete points)

	Cigánd (%)	**Révleányvár (%)**	**Halászhomok (%)**	**Lázbérc (%)**	**Rakaca (%)**
Bishop	43.6	21.9	36.9	10.2	12.3
Janbu	43.8	19.1	31.5	14.3	16.4
Spencer	43.6	22.0	36.8	10.1	12.8
Morgenstern-Price	43.6	22.0	36.8	10.1	14.5
Average	**43.6**	**21.3**	**35.5**	**11.2**	**14.0**

Table 8: Changes in the factor of safety compared to a dry state, considering the effect of water (highest seepage line)

	Cigánd (%)	**Révleányvár (%)**	**Halászhomok (%)**	**Lázbérc (%)**	**Rakaca (%)**
Bishop	24.1	16.4	17.6	10.2	0.8
Janbu	24.1	14.6	14.1	13.8	1.8
Spencer	24.2	16.4	17.6	10.1	1.4
Morgenstern-Price	24.2	16.4	17.6	10.3	2.8
Average	**24.1**	**16.0**	**16.7**	**11.1**	**1.7**

We can see from the table that the pore water pressure influences the safety factor. Using the Slope module, the highest difference was experienced in case of the embankment of Cigánd, which was caused by the shear strength parameters and the geometry of the embankment.

During our examination, we had the opportunity to compare the two programs used. We limited the comparison to the Spencer method because this method is found in both software. The differences are shown in Table 10, where we can see that the relative difference is quite small, so we can state that these two methods calculate a similar factor of safety values. Considering the data request, we can state that the using of GMS is easier, but the structure of the Slope module is more transparent. The GMS module can be a better solution if we have few data.

Table 9: Comparison of the factor of safety values calculated by GMS and SoilVision programs (Spencer method)

	GMS, UTEXAS	**SoilVision, Slope**	**Relative difference in factor of safety (%)**
Cigánd	2.971	2.555	14.00
Révleányvár	1.943	2.111	7.96
Halászhomok	2.815	2.738	2.81
Lázbérc	1.561	1.595	2.13
Rakaca	2.679	2.508	6.82

Conclusion

We modelled the seepage conditions of three flood protection embankments near the Tisza River and the Lázbérc and Rakaca reservoir dams, complemented with a slope stability test considering the subsoil. During our examination water level was correlated to the standard flood level in the case of embankments, while the correlation was to the maximal operational water level for the Lázbérc and Rakaca reservoir dams. During the modelling procedure, we assumed permanent, so-called steady-state conditions. The complexity is characteristic to the geometry of flood protection embankments, the parameters of embankment's materials we took over partially from previous works, and partially we derived them from the national technical directive.

For the valley dams, the characteristic cross-sections identify the constructional elements built in to control the leakage. In the case of embankments, it was noticeable that the position of streamlines depends greatly on the characteristics of subsoil, the thickness and the leakage factor. The various seepage effects of the drainage elements are visible at the valley dams. We prepared leakage models for several cases to explore the effects of mesh density and the width of the embankment foot, which are important parameters in the modelling procedure. As mesh spacing increases, the increase in total flow rate can be seen, and with the decreasing of the mesh spacing, streamline contours are even more accurate. We compared the total flow rate results with those of a previous study in which the subsoil characteristics were not considered. We found that results for the total flow rate and the seepage conditions were highly influenced by the consideration of subsoil, which is confirmed by experiences in the field. Therefore, we can say that in the case of embankments, we get a better view of the seepage conditions, if we consider the subsoil. We used two programs in the slope stability investigation – the UTEXAS module of Groundwater Modelling System version 10 and SoilVision's Slope module – and carried out the examinations with multiple slope stability calculation methods. We examined two cases, a dry state and a wet state, to examine the effects of water pressure, and seepage on slope stability. We had the opportunity to compare the two programs in regard to their results and usage.

As a summary, we can say that useful results were obtained with the modelling procedures, which can provide great help for experts in the water industry. Flood protection works require continuous activity, and fast numerical computation methods cast light on potential upcoming failures and thus may help to mitigate or avoid catastrophes.

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