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Sustainable levee construction along the Danube River

E. Koch[1], R. P. Ray[2], L. Tonni[3], M. Marchi[4]

[1]*Associate professor, Széchenyi István University, Győr, Hungary, email: koche@sze.hu*

[2]*Professor, Széchenyi István University, Győr, Hungary, email: ray@sze.hu*

[3]*Associate professor, University of Bologna, Italy, email: laura.tonni@unibo.it*

[4]*Senior assistant professor, University of Bologna, Italy, email: michela.marchi@unibo.it*

ABSTRACT

Nowadays' changing weather conditions and the resulting increasing flood levels make flood protection improvement essential. In Hungary, in the Szigetköz floodplain area, a complex water resources management unit of the Upper part of the Danube River, the rehabilitation of the water levels, and the setting back of the settled low and middle water levels had become necessary. It has been achieved by relocating the estuary of the Mosoni-Danube River and constructing a complex water control structure. A new ~1.5 km long levee connects to the structure. Due to a large volume of fine-grained blanket material on the site, the possibility arose to build a section of the levee using the blanket material without applying a cut-off wall to prevent water flow through the levee. The geotechnical parameters of the available local material were based on a complex site investigation program. According to the results of the field and laboratory tests, the blanket layer was suitable as fill material and could be compacted to the required 90% degree of compaction using standard machinery and procedures. Plaxis 2D software using fully coupled flow-deformation analysis, imitating the previously registered flood waves, modeled seepage and stability behaviour to evaluate the ultimate limit states of the levee constructed from the blanket material. The analysis proved the adequacy of the blanket material, avoiding the necessity for a barrier within the embankment. The use of local blanket material as fill eliminated the need to excavate and transport additional material, reducing environmental impact, shortening construction time, and saving costs on the project.

Keywords: blanket layer, flood, numerical modelling, saturation, seepage, transient flow

1 INTRODUCTION

In Hungary, in the Szigetköz floodplain along the Danube River, until 1992, the level of the groundwater was uniform, controlled by the natural water level fluctuation of the Danube (Kovács et al., 2015). After 1992, a large hydroelectric dam diverted a large portion of the river flow, leaving the main channel drastically lower. The main channel is now in a gaining condition as it draws water from the surface aquifer. This condition imitates the forecasted impact of climate change on the region. The complex water resources management of the Upper part of the Danube River, the rehabilitation of the water levels, and the restoration of low and middle water levels to their former condition had become necessary. It has been achieved by relocating the estuary of the Mosoni-Danube River and constructing a complex water control structure. A new ~1.5 km long levee connects to the structure. The system is further complicated by inland water control canals nearby. Figure 1 shows the site before and after the construction that added controls to the Mosoni channel, re-routed the internal canal and added stronger flood protection to both sides. The structure connects the main shoreline to Torda Island and elevates the Mosoni channel about 2m. In addition to the hardened levee segments, an extensive system of earthen levees now protects both shorelines of the Mosoni channel upstream from the control system.

Initially, designers anticipated using the granular material collected from the structural excavations. A low conductivity core built using a Cutter Soil Mix technique would provide a seepage barrier within the earth embankment. However, the material balance estimation at the project's beginning indicated a large volume of fine-grained blanket soils on the site. So, designers wanted to consider using the blanket material for a section (0+000-0+650 km) of the levee and leave out the soil mix core that would reduce seepage through the levee. The levee has a typical height of ~7.0 m, a crest width of 6.0-10.0 m, a slope of 1:3 on each side, and a 10.0 m wide berm with 10% sloping connected to the levee. The objectives of this study are (1) to describe the suitability of the blanket material for embankment fill (2) to control the ultimate limit states using time-domain Fine Element (FE) analysis.

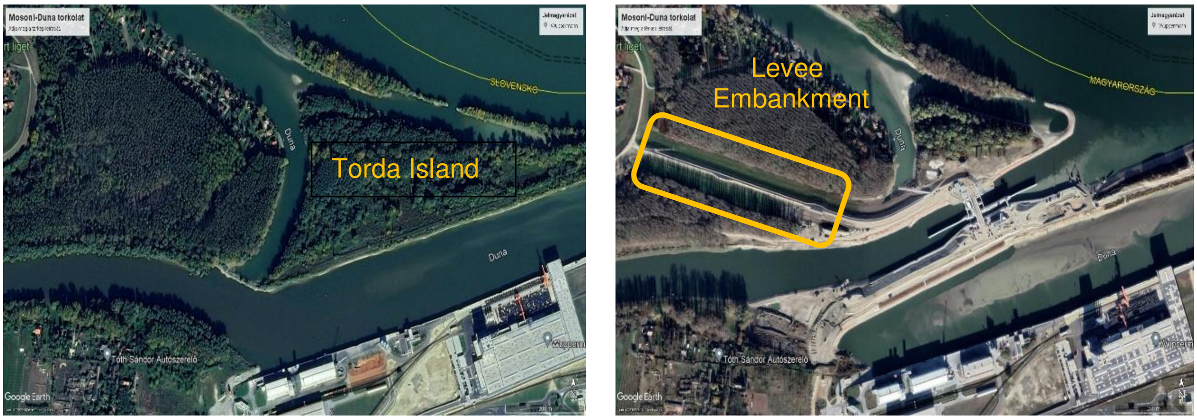


Figure 1. *Aerial photo of the construction site (left side before, right side after construction)*

2 GEOTECHNICAL CHARACTERISATION OF THE CONSTRUCTION SITE

The Danube reaches the Carpathian basin at Devin gate, where the upper section of the Danube ends. There, the velocity of the river reduces and creates a unique inner delta in the Szigetköz-Csallóköz region (Ács et al., 2020). The Szigetköz area is a part of the Little Hungarian Plain, which developed in the course of the Middle Miocene subsidence and the filling up of the alpine orogeny between the Eastern Alps and the Western Carpathians. The uppermost 100-500 m sedimentary sequence of the Szigetköz is characterized by sand and gravel sediments. The surface gravel, characterized by high hydraulic conductivity is underlain by fine-grained sediments with low conductivity, the sand, silt and clay deposits of the Upper Pannonian. An overburden Holocene layer of 0-6 m thickness covers the surface of the alluvial fan and is characterized by a medium permeability (Trásy et al., 2020).

The Site Investigation Report (FUGRO, 2019) describes the surface covered by a fine-grained blanket with variable thickness (~1,0-5,0 m) consisting mainly of clayey/sandy silt. Beneath the blanket layer, a compacted coarse-grained sandy gravel or gravelly sand layer penetrated to a depth of ~20.0 m. This layer possessed a high hydraulic conductivity and high bearing capacity. Many of the borings revealed clays below the surface, most likely representing the upper eroded zone of the Pannonian formation. Typical for floodplain soils, groundwater is present close to the natural surface.

To support the soil characterisation, field crews drilled 21 boreholes, pushed 9 CPTu (static) soundings, 3 SCPTu seismic soundings, and drove seven dynamic probing tests over the construction area. Geophysical measurements further defined the location and extent of high and low-conductivity soils along the 1.5 km-long levee.

Figure 2 shows one of the CPTu sounding's results, performed on Torda Island, showing the cone resistance (q_c), friction ratio (R_f) and the soil behaviour type index (SBTn) as a function of the depth. It is clearly visible that the surface is covered by ~2,6 m thick fine-grained blanket material. Below the clayey silt and silty clay soils, the typical river sediments of the Danube continue to the termination of the sounding. The cone resistance of the blanket material is $q_c \approx 2{,}0$ MPa, the state of the soil is medium stiff.

Figure 3 shows the measured electrical resistivity for the levee's first transverse section from the levee's base to the river centerline (0+000-0+750). Note that, on the vertical axis, mBf means the altitude above the Baltic Sea level. The data show:

– from the beginning 0+000 to section 0+500, the surface is covered by a 4-5 m thick cohesive soil with low resistivity (red zone),

- a layer of sandy gravel with variable grain size lies beneath the cohesive soils (green),
- below the granular layer with variable thickness decreasing resistivity is typical, indicating that the granular layer has settled on a layer of bedrock material (yellow-green),
- beyond the 0+500 section, higher resistivity appears on the surface (green-grey), followed below by a gravel layer with much higher resistivity than before (brown-grey).
- the Pannonian basement appears at ~40 m below the surface, where resistivity decreases with depth.

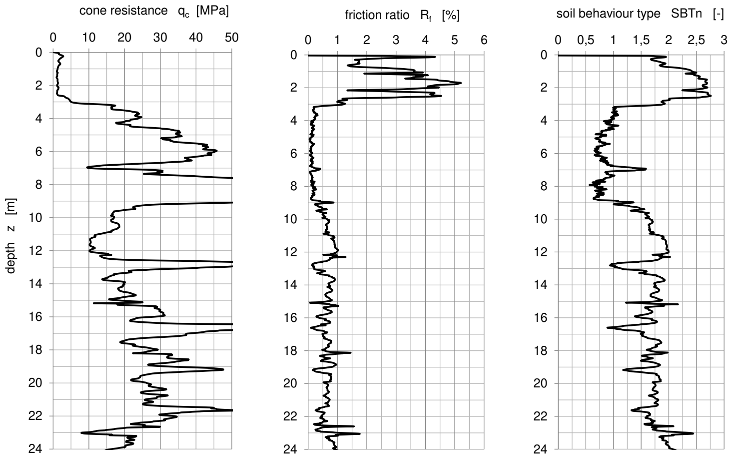


Figure 2. *Results of a CPTu sounding*

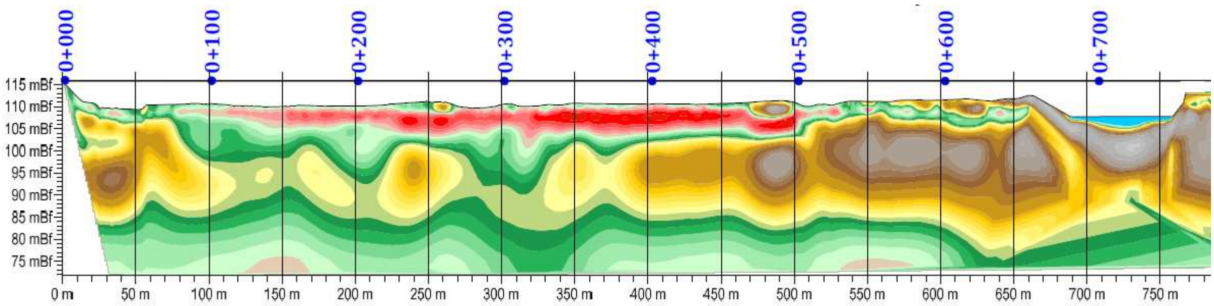


Figure 3. *Electrical resistivity profile on section 0+000-0+750*

3 BLANKET LAYER AS FILL MATERIAL

Fine-grained blanket material provided the primary source for a section of the 1.5 km long levee (0+000-0+650). During the excavations for the structure, visual inspection revealed the 1.0-4.0m-thick blanket layer. Based on the CPT soundings, the blanket layer consists of clayey silt, silty clay, or in some spots, sandy silt. Soundings showed that the blanket layer density was mainly medium dense, with occasional soft and stiff zones. The cone resistance of the blanket layer hardly varies; the average value is $q_c \approx 1.4\text{-}2.0$ MPa. Based on the Dynamic Probing Test, the number of blows for 20 mm penetration is less than 5.

The construction site contained 21 boreholes. According to the EUROCODE 7 (EC 7) Classification system based on grading curves, the samples are clayey silt, sandy, clayey silt, silt, sandy silt, and clayey sand. Figure 4 shows the grain distribution curves of samples from the blanket layer. The sand content varies from 12 to 73 %, with the silt content between 21 and 70 %. The figure suggests that silt is the dominant particle. The clay content is less than 20 %, and the gravel is negligible. The blanket layer is considered sandy silt, with varying degrees of sand and clay.

For the geohydraulic analysis, the hydraulic conductivity of the blanket layer is crucial. Its value was estimated from the grain size distribution curves using the Zamarin method (Zamarin, 1928). The method predicted conductivities between k=0.05-0.2 m/day. The higher value corresponds to sandy silt, the lower to clayey silt.

According to the practice, roadway specification (e-Út 06.02.11) classifies materials at a construction site. Primarily intended for road construction, it also applies to railway construction. We applied this system since there is no other standard for hydraulic engineering.

According to the specification, the blanket layers as general fill material are classified as M-3 and M-4, i.e., suitable and acceptable. This classification means that the soil can be compacted to a compaction degree of 90-95 % by applying general compaction machines and procedures, and the embankments' behaviour (stability, self-compaction, durability) can meet the requirements. Regarding compatibility, the blanket layers are classified as T-2 and T-3, i.e., moderate and difficult to compact. Also, according to the mentioned specification, the water sensitivity of these materials can be described as
- erosion sensitive,
- no volume change potential,
- sensitive to frost,
- moderate and slow permeability.

Based on the characterisation of the blanket material, the material properties are summarised in Table 1. To estimate soil parameters, we assumed a 90% degree of compaction and homogenisation of the excavated soils. To adjust to the PLAXIS 3D model of the water control structure, the HS-small material model was used for the seepage and slope stability analysis (Benz, 2006; Brinkgreve &Vermeer, 2014).

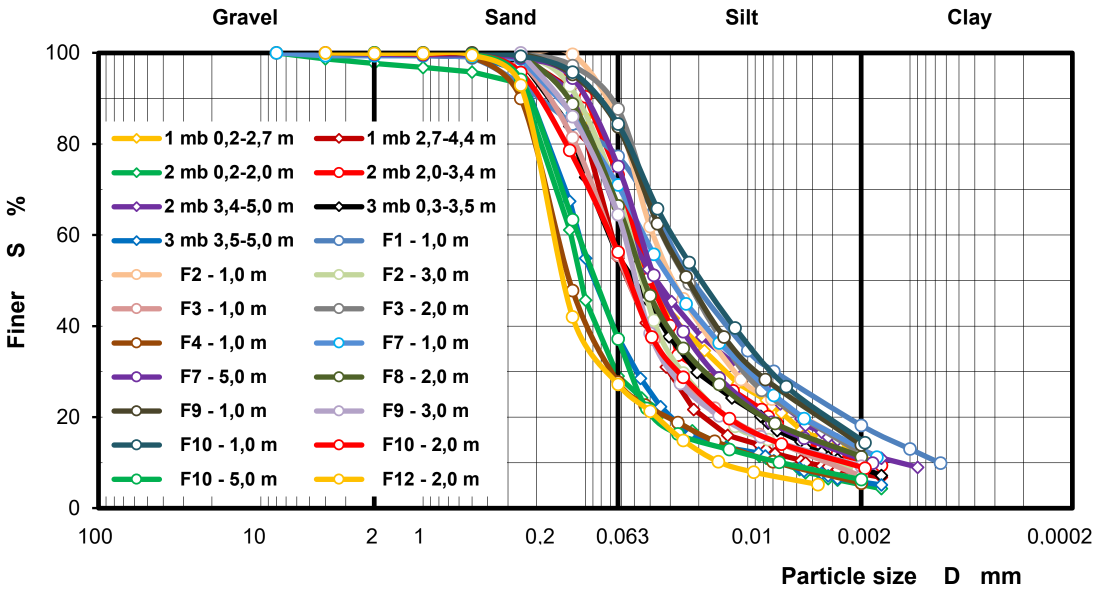


Figure 4. *Grain size distribution curves of the blanket layer*

Table 1. *Material properties of the blanket material*

Material	γ_{unsat} kN/m³	γ_{sat} kN/m³	E_{oed}^{ref} MPa	E_{ur}^{ref} MPa	c'_{ref} kPa	φ'_{ref} °	$\gamma_{0,7}$ -	G_0 MPa	k m/day
0_fill (blanket layer)	19.8	20.0	8	24	18	18	1E-4	60	0.05/0.20

4 MODELLING APPROACH

The International Levee Handbook (ILH, CIRIA, 2013) gives a state-of-the-art covering nearly all problems related to levees. For analysis of seepage, numerical modeling is recommended in addition to conventional methods. A single FE (Finite-element) model can apply to levee design, stability analysis, seepage analysis through and underneath levees, and analysis of seepage forces.

The levees are generally considered as Geotechnical Category (GC) 3 due to the high risk. Projects classified as GC 2 can only occur on sites with advantageous conditions and moderate risk. For the investigated project Geotechnical Category 3 was determined.

The use of design approach 3 has been decided in the Hungarian national annexe of Eurocode 7 (EC7) for overall stability problems as in other countries. This is exceptionally reasonable for levees because no partial factor should be used for actions. The partial factor used for shear strength parameters is 1.35. Geotechnical finite element software performs stability analysis using the ϕ-c reduction method, also referred to as Safety Analysis by Plaxis, which corresponds to design method 3. The resulting safety factor must be compared with the partial factors defined by the standard, $\gamma_{\phi,c}$=1,35.

For characteristic water levels on the waterside, the so-called standard flood level (MÁSZ) given in Hungarian governmental regulations for all rivers can be accepted as an estimated upper level according to EC-2.4.5.3.(1)P in EC 7-1. The water level boundary condition on the waterside, MÁSZ+1.0m, can be used as prescribed in the regulations mentioned. Analyses have shown that these levels correspond to a recurrence interval of about 1000 years. With this approach, all EC requirements given in paragraph EC-2.4.6. are fulfilled (Szepeshazi et al., 2015).

EN1997-1, Section 10.2 requires checking the uplift limit state (UPL) if a low conductivity layer (such as the blanket layer) lies on the ground surface. The failure mechanism is pore pressures lifting the blanket layer upward. In our case, the only resisting action is the self-weight of the blanket. The UPL limit state will apply partial factors of 1.25 to soil resistance and 0.9 to the blanket weight resistance (negative action). However, FEM analysis automatically considers the UPL failure mechanism, so a separate check is unnecessary. The hydraulic failure condition (HYD) requires careful examination of the seepage regime and judgement concerning levels. HYD failure may occur due to heave, internal erosion, or piping. These failure modes are driven by groundwater moving upward out of the soil. Simple mechanical equilibrium no longer explains the failure process. The more difficult judgement occurs when 1.35 partial factor for soil shear strength in overall stability, the required safety factor against UPL, determined by the above two partial factors (1.25 and 0.9), is also satisfied.

The HYD limit state can occur through heave, internal erosion, and piping. The check for heave is similar to the UPL, but soil shear resistance is neglected, which is not reasonable for levees. But, if the shear resistances are involved in the analysis, the suggested check for heave is the same as for the UPL. But, UPL should not be calculated independently when analysing the overall stability by FEM. Internal erosion and piping should be checked as well. Hydraulic gradients can be determined from a flow net and should be compared to critical hydraulic gradients. The safety against hydraulic failure cannot be checked directly by FEM software; it has to be controlled separately from the results of the runs by "manual calculation."

We applied a fully coupled flow-deformation analysis using PLAXIS 2D to evaluate the overall stability and hydraulic failure. Table 2 summarises the thickness and geotechnical properties of the layers determined from the results of the site investigations and laboratory tests. Figure 5 shows the geometry and mesh model.

Table 2. *Material properties of the* layers

Layers	**thick m**	**γ_{unsat} kN/m³**	**E_{oed}^{ref} MPa**	**E_{ur}^{ref} MPa**	**c'_{ref} kPa**	**φ'_{ref} °**	**$\gamma_{0,7}$ -**	**G_0 MPa**	**k m/day**
1_sandy silt	1.3	19	6	18	18	18	1.5E-4	40	0.04
2_medium clay	1.0	20	8	40	28	14	1.8E-4	60	6E-5
3_fat clay	3.0	20	4.2	20	10	18	2.2E-4	30	1E-5
4_gravelly sand	13.0	21	20	60	6	33	1.0E-4	100	1.0

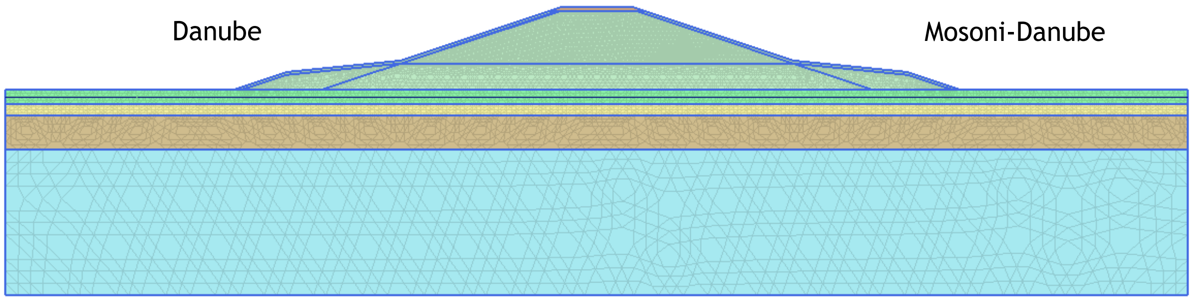


Figure 5. *PLAXIS 2D Geometry and mesh model*

The levee section (0+000-0+650) must withstand flood waves from the Danube on one side and the Mosoni-Danube on the other. Each has its unique flood wave elevation. After investigating the flood waves of the Danube and Mosoni-Danube Rivers that have occurred during the last decades, the following scenarios were considered separately in the seepage analysis. The Danube flood wave starts at 108.50 mBf (meter above the Baltic sea level), rises to 116.8 mBf over 6 days then remains at that level for one day. The flood wave falls in the same manner. For scenario A, the Mosoni-Danube remains at 108.50 mBf, the so-called rehabilitation (permanently assured) water level. In scenario B, the water rises from 108.5 to 110.0 mBf over 3 days, remains there for 1 day, and then falls back over 3 days. Scenario C rises from 108.5 to 112.0 over 3 days, then remains at that level for 6 days, mimicking a closure of the structure. Then, the level falls back to 108.5 over three days. The final scenario has the Mosoni-Danube rising and falling over the same time period as the main Danube, but to a 1-day peak of 116.3 mBf to simulate flood waves that coincide on both sides. The water levels are summarised in Table 3 and illustrated in Figure 6.

Table 3. *Water levels at the scenarios*

Scenario	**Danube water level mBf**	**time day**	**Mosoni-Danube water level mBf**	**time day**
A	116.8	6+1+6	108.5	-
B	116.8	6+1+6	110.0	3+1+3
C	116.8	6+1+6	112.0	3+6+3
D	116.8	6+1+6	116.3	6+1+6

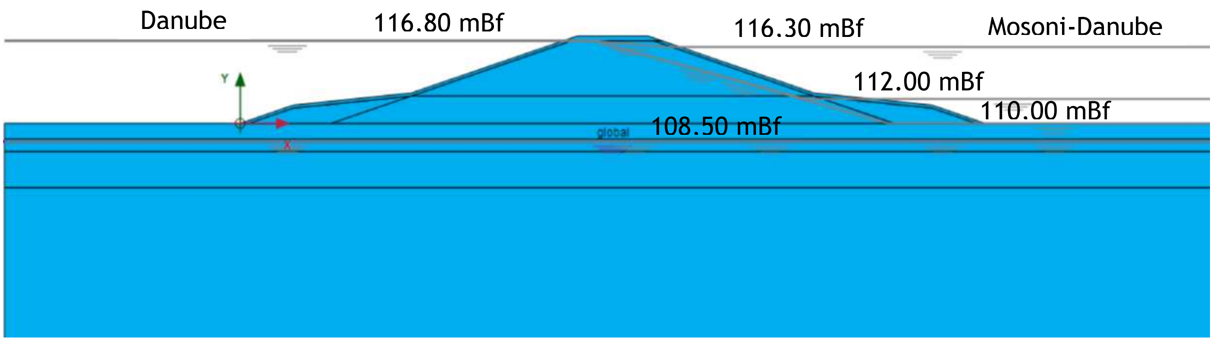


Figure 6. *Definition of the water levels*

5 RESULTS

Based on the laboratory test results, the blanket layer's hydraulic conductivity varies between k = 0.05-0.2 m/day. Hydraulic conductivity values of k = 0.05 m/day and k = 0.2 m/day applied to the blanket layer allowed us to study the effects of conductivity.

Figure 7 shows the deformed finite element mesh (magnified for clarity) for scenario A. The following observations relate to this condition:

- On the left side, flood waters exert a buoyant force on the levee's slope during the 6-day rise, lifting the embankment.
- Uneven horizontal seepage forces push the embankment toward the Mosoni-Duna side.
- The toe of the embankment on the Mosoni-Danube side rises slightly, but no heave occurs.
- The subsoil experiences deformation to a depth of 5-6 m.
- The phreatic surface also does not penetrate very far into the levee's "upstream" face. This is due to the low hydraulic conductivity of the blanket material.

On the right side of the figure, the 6-day fall causes different patterns:

- The levee moves towards the Danube side due to seepage forces from water exiting the "upstream" face.
- On the Danube side, the natural ground surface rises slightly, but no heaving occurs.

- Near the same area, the levee toe also rises slightly, but again without heaving.
- The phreatic line moved downward, indicating that seepage did not penetrate the levee.

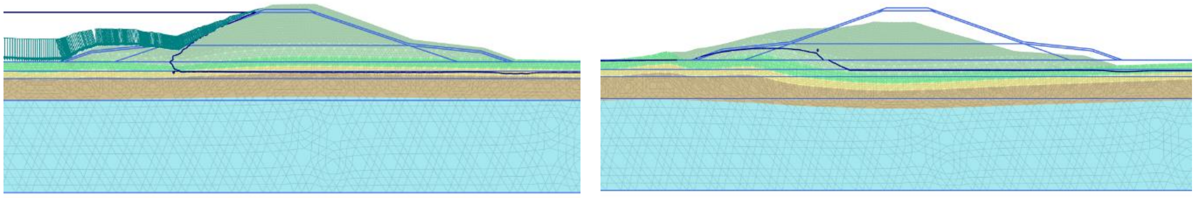
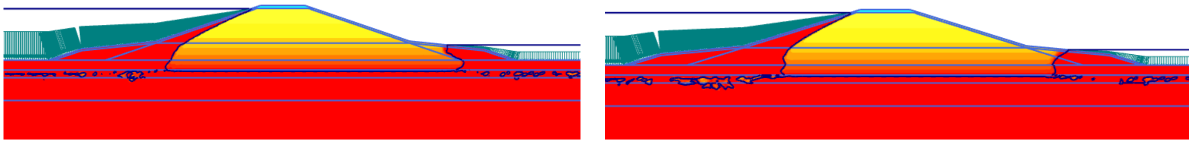


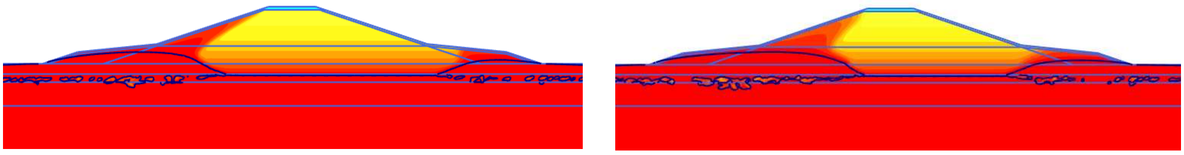
Figure 7. *Deformed mesh at peak water level (left) and after the fall (right)*

Figures 8 and 9 show the evolution of the levee saturation for scenario C after 7 days and 13 days, respectively. Both figures compare the effect of hydraulic conductivity on moisture migration. The left side has a lower permeability (k = 0.05 m/day), and the right has a higher one (k = 0.2 m/day). The unsaturated model applied for this analysis is based on van Genuchten. Soil classification determined estimates of initial saturation in the levee (5 types, from coarse to very fine) provided as input. Red shading indicates 95-100% saturation, and yellow means ~70%. The levee, constructed from blanket material, does not fully saturate when inundated by an "average" Danube flood. The fully-saturated zone extends from the edge of the levee crest on the Danube side to about one-third of the base distance. Saturation in the upper section of the berm is 60-70% (yellow). The value of k affects the moisture movement only slightly.



k = 0.05 m/day – day 7 k = 0.2 m/day - day 7

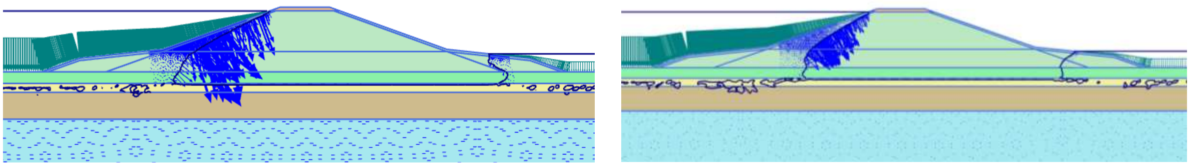
Figure 8. *Saturation at peak water level*



k = 0.05 m/day – day 13 k = 0.2 m/day - day 13

Figure 9. *Saturation after water level falling*

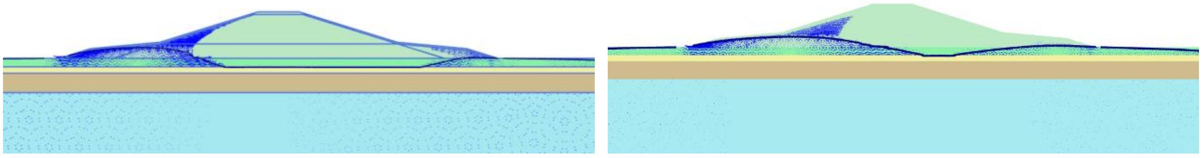
Figure 10 shows scenario C's seepage velocity vectors at the peak water level (day 7). The saturation line penetrates inwards from the slope on the Danube, with a velocity of $q_{max} \approx 3.0$ m/day near its middle. The low velocity cannot saturate the levee in 6-7 days. The 4-5m thick blanket layer (brown) allows minimal water seepage. The underlying coarse-grained layer shows some water movement, but it depends on nuances in the boundary conditions rather than water movement through the blanket layer. Hydraulic gradients near the levee toe on the Mosoni-Danube side indicate no danger of internal erosion or initiation of piping. Different conductivities (i.e. 0.05 and 0.2 m/day) have little impact on results.



k = 0.05 m/day – day 7 k = 0.2 m/day – day 7

Figure 10. *Seepage velocity vectors at peak water level*

Figure 11 shows the same scenario after the flood level on day 13. The only activity centres around the toe of the levee and the berm on the Danube side. The value $v=q_{max}$ is around 0.02 m/day, and the direction is slightly upwards and outwards. The berm, constructed by the blanket material, retains the water for a long time after the water level drops. There is practically no water movement in the 4-5 m thick blanket layer.



k = 0.05 m/day – day 13   k = 0.2 m/day – day 13

Figure 11. *Seepage velocity vectors after the fall*

Sometimes a large hydraulic gradient appears at a location of no interest to the design, e.g., at the surface of a deeper clay layer. Since the software will normalise its graphical results, the less-significant values overshadow more meaningful gradient values around the levee toe. Hydraulic gradient values may not accurately evaluate the potential for hydraulic (HYD) failure. Comparing seepage velocity and conductivity at different locations offers a better evaluation of internal erosion and piping. In the present case, the exit gradient on the Danube side is $i \approx v / k = 0.02 / 0.05 = 0.4$, with a nearly identical value for k = 0.2 m/day. This value is unacceptable for silty material; it might cause internal erosion and piping (Okeke & Wang, 2016).

As an alternative, we investigated how the seepage lines, velocity vectors and hydraulic gradients evolve if granular material (k=5 m/day) replaced the silty blanket material in the berms. Figure 12 shows the levee saturation with a granular berm, and the evolution of the seepage velocity vectors for the same condition. Both figures relate to the state after flooding (day 13). The saturation of the levee is similar to the fine-grained berm. The seepage velocity vectors indicate that water can freely flow through the granular berm as the water level falls. After falling, the seepage velocity in the gravelly berm is $v = q_{max}$ 1.7 m/day, from which the gradient $i \approx v / k = 1.7 / 5 = 0.34$, i.e. almost the same as before, but this is allowed for gravels (Wang et al., 2022).

The analysis showed that there could be gradients of ~0.8 at the boundary between the silty levee core and the granular berm. Although the software does not produce it directly, this value can cause colmation where the silt can migrates into the gravel, causing a blockage. A geotextile with a suitable filter opening between the two materials will prevent this from happening.

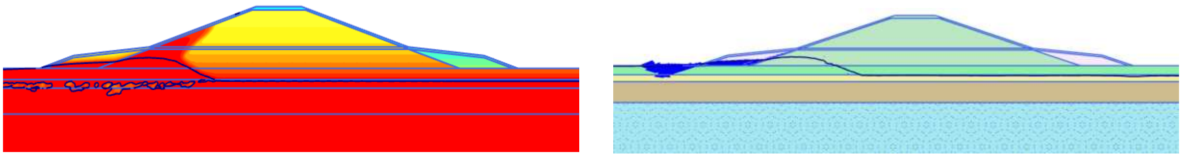


Figure 12. *Levee saturation (left side) and seepage velocity vectors (right side) with granular berm*

Figure 13 shows the slope failure mechanism due to rising water for variant A. The pore water pressures from the Danube side "push" the levee. The slip surface starts from the levee's crest and progresses to about 5.5 m below the surface (to the top of the granular layer). It ends at about 3-4 m in front of the levee toe on the Mosoni-Danube side.

Figure 14 shows the failure mechanism after the Danube's water level fall. As expected, a similar circular slip surface appears but on the Danube side. It starts from the levee crest, proceeds to about 5.0 m below the surface (to the top of the granular layer), and ends about 2-3 m in front of the levee toe on the Danube side.

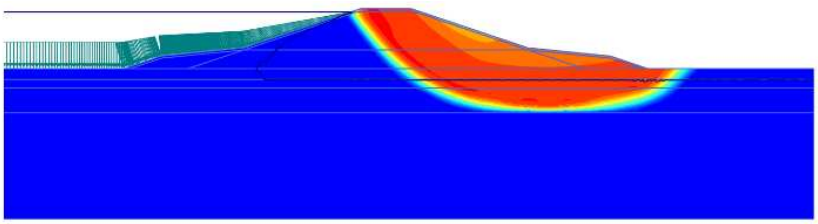


Figure 13. *Failure mechanism at peak water level*

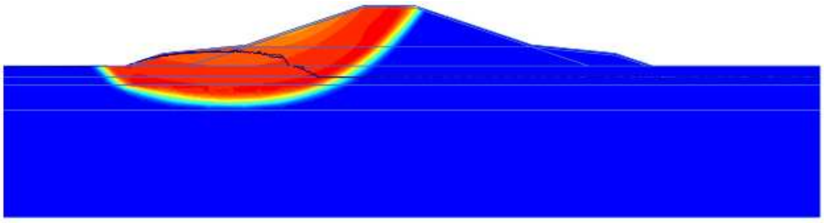


Figure 14. *Failure mechanism after the fall*

Very similar results were obtained for the other scenarios and are therefore not reported. Table 4 summarizes the safety factors against overall stability for each variant. In all cases, it is higher than the required γ=1.35.

Table 4. *Safety factors of the scenarios*

variant	peak water level γ	after flood γ
A	1.99	2.02
B	1.94	1.98
C	2.05	1.98
D	3.60	1.92

The long-term effect of the levee constructed from the blanket material was investigated by using steady-state groundwater flow analysis. Figure 15 shows the levee saturation with a granular berm, and the failure mechanism for the long-term condition for scenario C. Both figures relate to the state at peak water level. It can be seen that most of the levee becomes saturated but the safety factor against overall failure still remains γ>1.35.

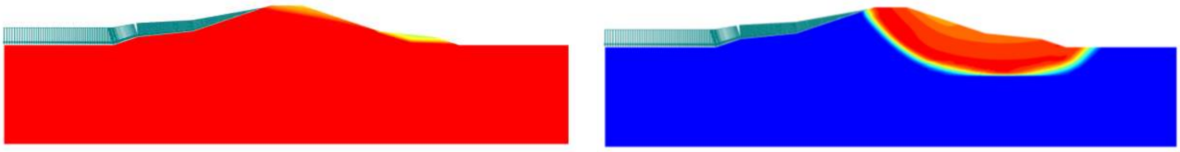


Figure 15. *Long-term levee saturation (left side) and failure mechanism (right side) at peak water level*

6 CONCLUSIONS

The complex water resources management of the Upper Danube River has required the recalibration of water levels and the adjustment of low and middle water levels. A solution has met those requirements by relocating the estuary of the Mosoni-Danube River and constructing a complex water control structure. A new ~1.5 km long levee connects to that structure. The original design called for a levee built from granular soils, excavated from the planned structure, and modified with a Cutter Soil Mix wall to reduce seepage. However, the large volume of fine-grained blankets on the site allowed a section of the levee made from blanket material without a cut-off wall.

The site investigations and laboratory tests indicate that the blanket layer is silt with varying sand and clay components. Its hydraulic conductivity varies between k=0.05-0.2 m/day. Overall, the blanket layer was suitable as fill material and could be compacted to the required 90% degree of compaction. However, due to its susceptibility to erosion, the soil requires increased attention from a geohydraulic point of view, and precautions were necessary.

The geohydraulic analysis assumed a low (k=0.05 m/day) and a high (k=0.2) permeability value, but the difference seemed insignificant. Analyses showed that the levee constructed from the blanket layer does not become fully saturated during an "average" Danube flood when either k value is applied. Based on the analysis, we can state:

- seepage is very low in the fined-grained subsoil,
- during drawdown, water will not readily flow out of the berm made from the blanket material,
- the highest gradients occur around the levee toe, i≈0,4, which is unacceptable for silty material,
- a granular berm generates a similar gradient but is more resistant to internal erosion,
- the results of the overall stability analysis are higher than the required 1.35,
- there is no risk of uplift.

As in the case of such flood protection works, we could not map all the surface soil zones, so silt and sandy gravel may be found next to each other during construction. In such cases, installing geotextiles on these interfaces is appropriate for filtering purposes. Otherwise, contact erosion at such interfaces and any local anomalies in the silt (plant remains, ruts, etc.) can trigger concentrated erosion, which can develop into a sand boil in such material. Therefore, it is advisable to stop sedimentation at the interfaces by filtration.

Taking advantage of the transient flow modelling, we have determined that blanket material is suitable for construction. However, the material in the berm should be gravel to ensure rapid drainage. The Plaxis software cannot analyse the risk of internal erosion, colmation, and piping since we can only infer the risk based on seepage velocity vectors and hydraulic gradients. Finite element analysis relies on accurate hydraulic conductivity estimates, so its determination is vital. The effect of conductivity variability requires careful evaluation through sensitivity analysis.

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