

## Reliability-based internal erosion analyses on the Szigetköz floodplain area

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**ABSTRACT:** In many parts of the world, flooding is the leading cause of losses from natural phenomena and is responsible for more damaging events than any other type of natural hazard. Hungary has long river levee systems along its two major rivers and their tributaries. Szigetköz island, part of the Little Hungarian Plain is located along the Danube River and is a "hotbed" of sand boil formation, mainly due to the combination of thick gravel layer beneath a relatively thin blanket of poor soil with variable thickness. Sand boils have a long history in this area where they recur at the same locations and water levels; some even have names. This paper presents the underseepage analysis based on an analytical method related to hydraulic failure in a specific Szigetköz floodplain area. A series of stability analyses assessed the impacts of subsoil conductivity, thickness, and floodwater levels. The results indicated that the risk of hydraulic failure increases as the leakage factor increases. Consequently, the impact of the blanket layer thickness becomes less significant. These findings can be utilized in other areas of the Szigetköz floodplain to produce underseepage hazard maps and identify sections vulnerable to hydraulic failure.

**KEYWORDS:** Internal erosion, levee, sandboil, Szigetköz floodplain.

### 1 INTRODUCTION

Flooding is a natural hazard which probably has the highest occurrence in time and space across the world, every year causing considerable damage in terms of loss of life and property (Michelazzo et al., 2018). The severity of its consequences is often intensified by factors such as climate change, urban expansion, and insufficient infrastructure, which underscores the growing importance of effective flood management.

Levees, floodwalls, and culverts are essential hydraulic elements within flood control and water management systems. Levees, which are typically earthen embankments constructed for flood protection, must be analyzed for a range of potential failure mechanisms. Such failures can be caused by overtopping, slope instability, external erosion, or internal erosion. Levee failures can be triggered by overtopping, slope instability, external erosion, or internal erosion (ICOLD and CIGB, 2017).

Overflowing and seepage represent two of the most common hydraulic failures that can initiate levee breaching (Nagy and Tóth, 2005; Morris et al., 2007). Overflowing may result in levee failure due to external erosion mechanisms, whereas seepage through or beneath a levee during flooding poses significant safety concerns when internal erosion mechanisms are present (Ozkan, 2003).

Internal erosion includes four mechanisms: backward erosion, suffusion, concentrated leak erosion, and contact erosion (CIRIA (2013). Among all internal erosion processes, backward erosion piping (BEP) is regarded as the principal failure mechanism for levees, constituting one-third of all pipe failures in the past century. BEP occurs when soil erosion begins at an unfiltered seepage exit and erodes backward along the interface of an erodible, nonplastic layer (e.g sand) and a cohesive cover layer as illustrated in Figure 1. Once erosion has initiated, particles may continue to gradually erode until a "pipe" has formed continuously beneath the structure, leading to possible collapse and subsequent failure of the structure (Robbins and van Beek, 2015). This phenomenon is particularly challenging to detect and mitigate because it occurs beneath the surface, out of sight from conventional monitoring methods (Brandl and Szabó, 2018).

This study assesses safety factors against hydraulic failure using the well-established "blanket theory." Stability analyses identified critical locations within the study area that are susceptible to hydraulic failure. The methodology can be applied to other regions of the Szigetköz floodplain, supporting

the development of underseepage hazard maps to pinpoint vulnerable sections. Additionally, the procedure aids decision-making for optimizing mitigation strategies along the upper River Danube in Hungary, where water levels have recently increased.

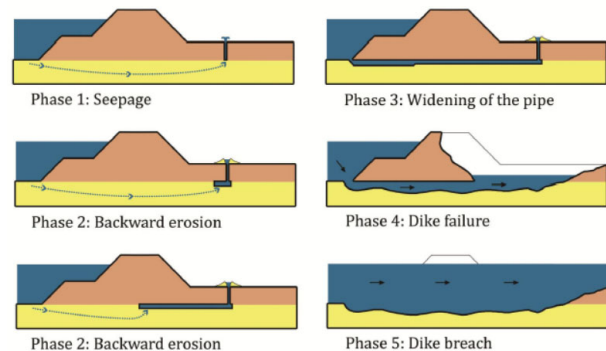


Figure 1. Illustration of the process of backward erosion piping (BEP) (van Beek, 2015).

### 2 METHODS

The erosional characteristics of soil can be examined through various approaches, including physical modeling (van Beek, 2015), numerical analysis (Robbins, 2016), and neural network-based techniques (Kuanda, 2015). Although advanced methods offer significant benefits, the geotechnical field still frequently relies on straightforward empirical or semi-empirical approaches (Rossi, 2021).

This research used the analytical method of underseepage analysis of a river embankment, the United States Army Corps of Engineers "blanket theory" approach (USACE, 2000). Based on this approach, the levee foundation can be generally subdivided into two layers, an overlying blanket layer and an underlying pervious foundation layer. Flow through the topstratum blanket layer is considered to be vertical, and flow through the pervious foundation layer is assumed to be horizontal. From this generic outline, a number of more specific design cases are identified (USACE 2000), which depend on the relative permeability of the blanket layer to the foundation layer (e.g., impervious, semipervious), and whether or not the blanket layer is present on the landside or riverside of the levee (Meehan and Benjasupattananan. 2012).

Fig. 2 shows the input variables that are used when performing an underseepage analysis of a levee following the USACE (2000) analytical approach. The method assumes a

homogeneous isotropic levee overlying a topstratum clay blanket, which can be divided into different zones: the riverside blanket ( $L_1$ ), the levee ( $L_2$ ), and the landside blanket ( $L_3$ ).

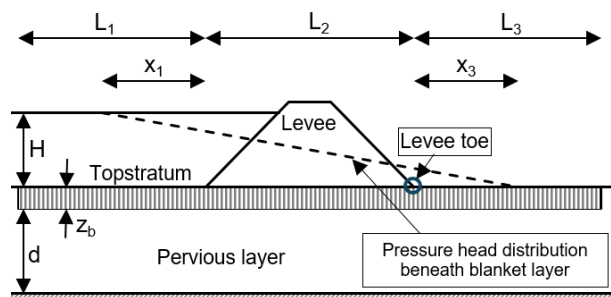


Figure 2. Idealized cross-section of the levee for underseepage analysis (USACE, 2000).

For the case where the riverside blanket and landside blanket soils are the same, and where  $L_1$  and  $L_3$  are finite distances to open seepage entrances and exits, respectively,  $x_1$  and  $x_3$  can be calculated as follows (USACE, 2000, Case 7c):

$$x_1 = \frac{\tanh(c \cdot L_1)}{c} \quad (1)$$

$$x_3 = \frac{\tanh(c \cdot L_3)}{c} \quad (2)$$

where,  $x_1$  is the distance from riverside levee toe to effective seepage entrance (m),  $x_3$  is the distance from landside levee toe to effective seepage exit (m),  $L_1$  is the distance from the river to the waterside levee toe (m),  $L_3$  is the length of the top layer on the landside (m). The parameter “c” characterizes the relative tendency for infiltration and exfiltration through the overlying confining blanket and is defined as:

$$c = \frac{1}{\lambda} = \sqrt{\frac{k_b}{k_f \cdot z_b \cdot d}} \quad (3)$$

where  $k_b$  = the permeability of the semi-pervious blanket,  $k_f$  = the permeability of the foundation layer,  $z_b$  = the thickness of the semi-pervious blanket and  $d$  = the thickness of the foundation layer. The parameter  $\lambda$  is called the leakage factor.

If the distance to the seepage blocks or seepage openings is relatively large, then the assumed boundary conditions tend to have only a minor effect on the analysis results. When  $L_1$  or  $L_3$  is very large (e.g., has a value that approaches infinity), an assumption of infinite blanket length can reasonably be made (Wolff, 2002). If this is the case,  $x_1$  and  $x_3$  can be calculated as follows (USACE, 2000, Case 7a):

$$x_1 = x_3 = \frac{1}{c} \quad (4)$$

The head beneath the landside blanket layer at the levee toe ( $h_0$ ) can be expressed:

$$h_0 = \frac{H \cdot x_3}{x_1 + L_2 + x_3} \quad (5)$$

where  $H$  is the net head on levee (m).

The Factor of Safety (SF) can be expressed:

$$SF = \frac{i_{crit}}{i_0} = \frac{i_{crit} \cdot z_b}{h_0} \quad (6)$$

where  $i_{crit}$  is the critical exit gradient,  $i_0$  is the upward gradient through the blanket layer. The critical gradient is defined as  $i_{cr} = \gamma' / \gamma_w$  where  $\gamma'$  is the submerged unit weight of the soil and  $\gamma_w$  is the unit weight of the water.

### 3 STUDY AREA ON THE LITTLE HUNGARIAN PLAIN

#### 3.1 Geology

The Little Hungarian Plain (LHP, Kisalföld in the Hungarian language) is a 6 000 square kilometers depression located in central Eastern Europe, fed by the River Danube and its tributaries (Rábca, Rába, Lajta and Marcal). With a total length of 2 900 kilometers, from its sources in the Black Forest in Germany to its delta on the Romanian coast of the Black Sea, the Danube is the oldest and the second longest river in Europe (Figure 3.). The landscape of the Kisalföld is that of the typical Hungarian steppe, with large areas of wetlands, although most of them have been recently drained for agricultural purposes (Szabó, 2005).

The Kisalföld is an interior plain surrounded by the Carpathians to the north and to the east, by the Dinaric Alps to the south, and by the Eastern Alps to the north-west. The River Danube made its appearance in the Little Hungarian plain at the end of the Pliocene (so-called Pannonian; 2.5 m years ago), accumulating up to the Mindel-Riss interglacial period of the Pleistocene (0.25 m years ago) an enormous alluvial fan. Since Middle-Pleistocene times (0.13 m years ago), the central and northern parts of this fan have subsided intermittently, whereas its southern sector has been uplifted, resulting in the formation of terraces along the Danube. Sediment forming the ancient (Pleistocene) alluvial fan has been therefore preserved on the Parndorfer-plateau in Austria, as well as on the highest ranges of the Győr-Tata Terrace Land. During Holocene times the Danube deposited a new alluvial fan. This younger sediment lies over Pleistocene deposits in the core of the new fan, whereas in other parts of the system they are found side by side (Pécsi, 1975).

Geological maps show how the sediment forming the youngest sequence in the evolution of the Danube's alluvial fan in the Kisalföld mainly consists of fluvial gravel, sand and clay deposited in a spectacular meander belt which can be observed in Szigetköz (Figure 3.). Peat layers and dark organic mud are deposited in paludal areas and in oxbow lakes formed in abandoned meanders. Since river regulation was undertaken in the last century, the large amount of sediment transported by the Danube has accumulated in the area confined by flood-protecting dams, resulting in the gradual elevation of the sediment's level (Kaiser, 1989). From recently acquired well and geophysical data, it is known that the total thickness of Quaternary fluvial sediment overlying the marine Pliocene deposits ranges between 38 and 700 m in this part of the Danube (Göcsei, 1979).

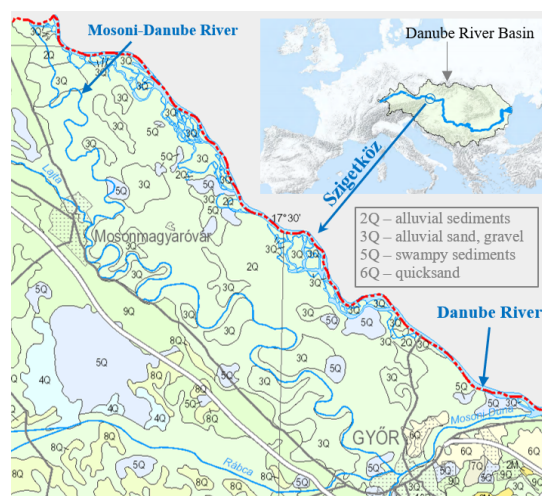


Figure 3. Location and surface geological map of the floodplain.

### 3.2 Soil properties

During the last decades, several sand boils have occurred along the upper part of the Danube River during floods. Following the flood events, site investigation programs were carried out, and laboratory tests were performed to deduce the stratification of the sections. Several boreholes and CPTu soundings were pushed to depths of ~10-15m. Additionally, surface geophysical measurements to depths of ~15m transected the site.

Laboratory tests on borehole samples revealed two different types of soils: the topstratum consists of silt and clay mixtures with low or medium permeability from the Holocene Age, the pervious layer contains the extensive deep layer of sandy and gravelly coarse sediments beneath the Danube.

Across the area under investigation, the thickness of the blanket layer varies between  $z_b=1.5$  m and  $z_b=3.5$  m with an average  $z_b=2.5$  m. The hydraulic conductivity of the blanket layer ranges between  $k_{b\min-max}=0.001-0.9$  m/day, with an average of  $k_{bav}=0.09$  m/day. The highly permeable aquifer lies below the blanket material, with an average hydraulic conductivity of  $k_f=86$  m/day.

Figure 4. shows some of the grain-size distribution curves of the semi-pervious blanket and aquifer samples, respectively.

The basic dimensions of the investigated levee are crown width = 6.0 m, the height of the levee = 4.8 m, and base width = 37.7 m. The simplified cross-section of the analyzed case appears in Figure 5.

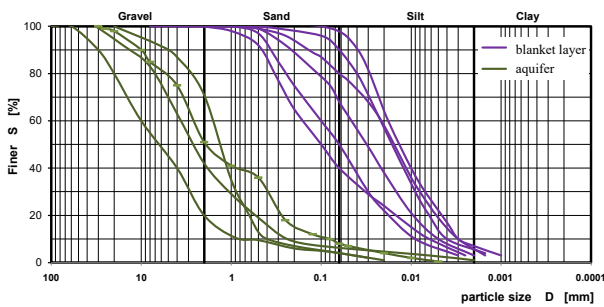


Figure 4. Grain size distribution curves of topstratum and aquifer.

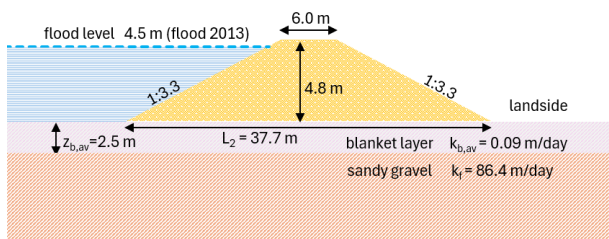


Figure 5. Simplified cross-section of the investigated area.

Based on the site investigations and laboratory test results, Table 1. summarizes the input data for the analysis of the investigated case. Table 1 lists the minimum, maximum and average values for the top layer's thickness ( $z_b$ ), hydraulic conductivity ( $k_b$ ) and auifer's hydraulic conductivity ( $k_f$ ).

Table 1. Data for analysis.

Parameter	Symbol	Min	Max	Av.	Unit
Lengths	$L_2=L_3$	-	-	1000	m
Aquifer thickness	$d$			50	m
Blanket thickness	$z_b$	1.5	3.5	2.5	m
Blanket permeability	$k_b$	0.001	0.9	0.09	m/day
Aquifer permeability	$k_f$	8.6	532	86	m/day

## 4 RESULTS AND DISCUSSIONS

To apply the USACE (2000) analytical approach, a series of parametric analyses was conducted to demonstrate the impact of varying  $k_f$ ,  $k_b$ , and  $z_b$  on the model results.

Figure 6. shows the safety factors for different floodwater levels and blanket thicknesses. As it was expected, a higher floodwater level causes a lower safety factor. As the thickness of the semi-pervious blanket increases, the safety factor against hydraulic failure also increases. Considering the average thickness of the top layer ( $z_b = 2.5$  m), the levee becomes critical against hydraulic failure when the flood water level exceeds 4.0 m, which was the case, e.g., in 2024 along the Danube River in the Little Hungarian Plain. For a blanket layer having  $z_b=1.5$  m, the levee becomes critical at the flood water level of  $H=2.5$  m. For the topstratum of  $z_b=3.5$  m, the safety factor is higher than  $SF=1.0$ . For low flood water levels, such as 1.5 m, the safety factor related to  $z_b=3.5$  m is about 3x the safety factors related to  $z_b=1.5$  m. The differences in the safety factors decrease as the flood water level increases.

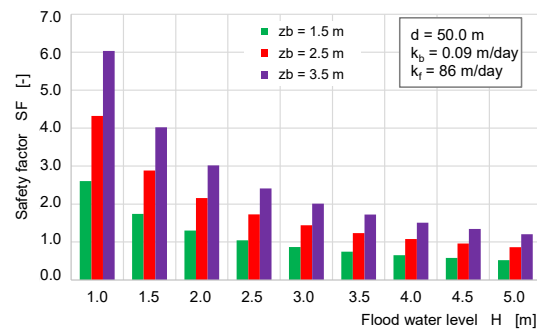


Figure 6. Relationship between flood water level and safety factor.

The grain-size distribution (see Figure 4.) and hydraulic conductivity results show a wide variation in blanket conductivity. Therefore, a sensitivity analysis examined the effect of conductivity and blanket thickness on the pressure head at the levee toe. To demonstrate the effect of the parameters, the leakage factor (see Equation 3.) ranged between  $\lambda \approx 10 - 10000$ .

Figure 7. illustrates the relationship between the leakage factor and the pressure head at the toe of the levee for various floodwater levels. In this analysis, an average blanket thickness of 2.5 meters ( $z_b = 2.5$  m) was considered. The results indicate that as the leakage factor increases, the pressure head at the levee toe also rises. When examining different floodwater levels, the curves are observed to move approximately parallel to each other. For low values of the leakage factor ( $\lambda < 500$ ), the increase in pressure head ( $h_0$ ) is significant, whereas for higher values ( $\lambda > 500$ ), the increase in  $h_0$  is more modest.

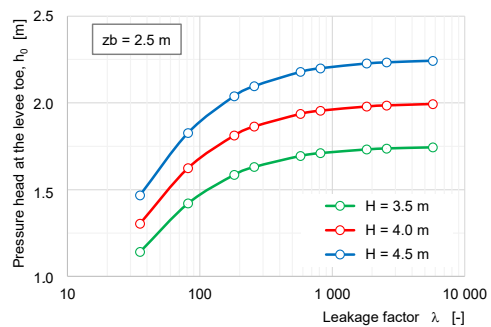


Figure 7. Relationship between the leakage factor and the pressure head at the levee toe.

Figure 8. illustrates the relationship between the leakage factor and the safety factor, considering an average blanket thickness

of 2.5 m ( $z_b = 2.5$  m). The results are plotted for various floodwater levels. It can be observed that as the leakage factor increases, the safety factor decreases. The reduction in the safety factor is significant for lower leakage factor values. However, beyond a certain value, approximately when the leakage factor exceeds 500, the reduction becomes minimal, and the safety factor stabilizes at almost a constant value.

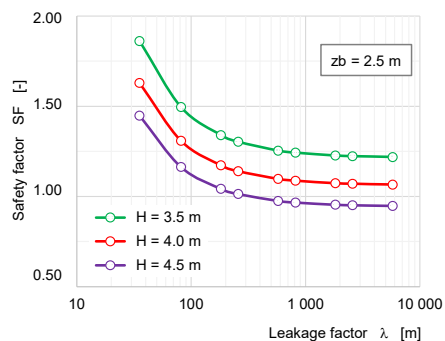


Figure 8. Relationship between the leakage factor and safety factor.

In this study, we analyzed the critical floodwater levels using a safety factor of  $SF = 1.0$ . The results are presented in Figure 9. It can be observed that as the leakage factor increases, the critical floodwater level decreases. Additionally, the critical water level stabilizes at a certain leakage factor, approximately  $\lambda \approx 500$ . These breaking points consistently occur at the same location. Based on the average leakage factor obtained from field tests, which is  $\lambda \approx 1100$ , areas lower than  $z_b \approx 2.5$  m may be highly susceptible to hydraulic failure.

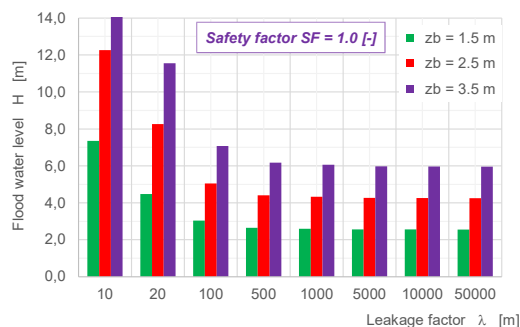


Figure 9. Relationship between the leakage factor and the critical flood water level.

## 5 CONCLUSIONS

In the design of flood protection system, assessing underseepage is crucial for determining the risk of failure due to soil erosion. In common engineering practice, the key input parameters — such as the hydraulic conductivity and thickness of the blanket and the aquifer — are subject to considerable uncertainty, as indicated in this study. The paper utilized the widely accepted "blanket theory" to a critical section of the Danube River levee located in the Little Hungarian Plain. Results from field and laboratory investigations revealed significant variability in the blanket material, necessitating a more detailed analysis of its effect on exit seepage.

The results of the underseepage analysis indicate that the thickness and hydraulic conductivity of the blanket material significantly influence the levee's performance. The higher the leakage factor, the higher the risk of hydraulic failure.

The results also indicated that the floodwater level corresponding to a Safety Factor of  $SF = 1.0$  decreases with increasing leakage factor. An area having blanket thickness approx.  $z_b < 2.5$  m, and leakage factor  $\lambda > 500$  might incur failure when considering an "average" flood event,  $H \approx 4.0$  m.

These findings can be utilized in other areas of the Little Hungarian floodplain to produce underseepage hazard maps and identify sections vulnerable to hydraulic failure. Additionally, the proposed method offers valuable support for decision-making in optimizing mitigation strategies against hydraulic failure along the upper part of the River Danube in Hungary.

## 6 ACKNOWLEDGEMENTS

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