Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Vulnerability of levees impacted by seepage near the Kettős-Körös River in Hungary

Edina Koch[1,2#], Mais Mayassah[1], and Richard P. Ray[1,2]
[1]Széchenyi István University, Department of Structural and Geotechnical Engineering, Egyetem sq. 1., 9026 Győr, Hungary
[2]Víztudományi és Vízbiztonsági Nemzeti Laboratórium, Pannon Egyetem, Körforgásos Gazdaság Egyetemi Központ, Nagykanizsa (Széchenyi István University)
[#]Corresponding author: koche@sze.hu

ABSTRACT

Due to climate change over the last decades, flood events in Hungary and other European countries have become increasingly frequent, with greater intensity and duration. These changes have impacted flood protection levees. A long-duration flood allows water to seep into the levees, saturating them and maximizing the potential for damage. Seepage through earthen levees is often observed during floods and can lead to levee failure if combined with internal erosion. This study assesses the levee vulnerability relative to seepage by considering the characteristic time scales of the seepage phenomena and the main factors driving them. The procedure is applied to the Körös sub-basin (Hungary), a site that has shown a continuous trend of increased water levels in recent years. Along the critical section of the levee, a comprehensive site investigation was carried out. The analysis has shown that hydraulic conductivity is the most significant parameter when considering seepage for levees along the Kettős-Körös River. The investigated dyke geometry shows higher vulnerability to lower water levels associated with a longer duration of flood water levels.

Keywords: Körös river; seepage; site characterization; time dependence

1. Introduction

Flooding is a common global natural disaster that poses significant risks to human life and property, resulting in substantial annual losses (Garrote et al., 2019). Globally, in 2018, natural disasters affected 61.7 million people, caused 10373 deaths and several billion US dollars in damages (CRED, 2018).

In several regions, the magnitude and frequency of flood waves have increased dramatically since long-term measurements and historical reports have existed (Brandl and Szabo, 2018). The risk of levee failure increases not only with the magnitude of a flood but also with its duration. For instance, the peak period of flood waves along the Hungarian section of the river Danube usually lasts one to three days, whereas its tributary, e.g., Tisza River or Körösök, frequently undergoes flood waves up to three or six weeks.

The main hydraulic function of a river levee is to reduce the risk of inundation by temporarily retaining water, keeping it out of the leveed area to a defined water level, and avoiding flooding conditions within this area. However, a levee might experience failure due to hydraulic and/or structural processes. As defined in CIRIA (2013), hydraulic failure occurs if water ingress into the leveed area (by through-flow, overflow, or overtopping of the levee) occurs before the planned protection level is reached and without prior damage to the levee. The structural failure occurs by a breach in the levee system that results from damages affecting at least one system segment. Structural failure can induce hydraulic failure and vice versa.

As reported in (Nagy and Tòth, 2005; Nagy, 2006; Morris et al., 2007), overtopping and seepage are the most frequent causes that might trigger the breach of a levee. Nagy and Toth (2005) conducted an extensive study of levee breaches in Hungary between 1954 and 2004. Based on analyses of 117 breaches, they determined that 88% of all breaches were caused by overtopping, piping, and loss of slope stability, while the failure mechanism could not be identified in 12 cases (Fig. 1). The high portion of overtopping could be explained by the floods occurred in the last century.

Breaches are the final phases of erosion or any other deterioration or damage mechanism following a gross enlargement of piping, slope instability, or an overtopping due to settlement of the crest or due to the formation of a sinkhole from a pipe in the embankment. A breach is a catastrophic collapse (CIRIA, 2013).

During floods, water seepage through and under the levee can become a safety problem if internal erosion mechanisms occur (Ozkan, 2003).

The primary function of the levee is to retain the water. Seepage through or under an embankment may reduce the levee's performance and cause failure. Especially in the early stage, the amount of water lost is often insignificant, and a small amount of seepage is acceptable. If it is left untreated, finer particles of soil will be washed out of the embankment or its foundation by water flow. As the soil's permeability increases, the rates of flow also rise, leading to a greater erosion of soil particles.

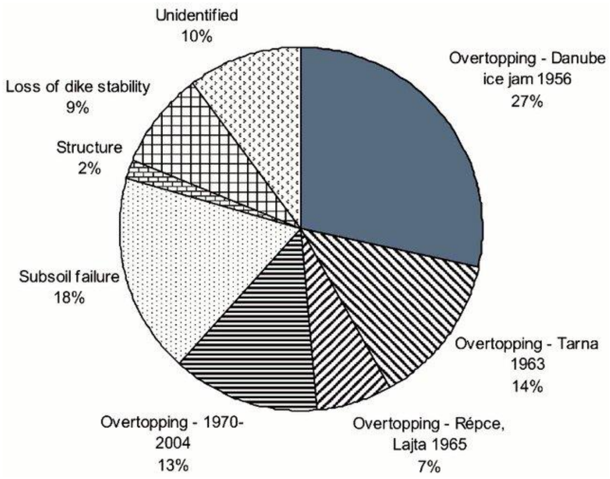

Figure 1. Distribution of failure mechanisms for levee breaches in Hungary between 1954-2004 (Nagy and Toth (2005).

Seepage will also increase the likelihood of slip failure because of changes to the soil–water regime within the embankment, causing a weakening of the fill materials or increasing the uplift pressures at the embankment toe. High porewater pressures can lead to increased seepage, hydraulic fracture, or instability, especially when they are higher than allowed for in the design. Uplift pressure in foundation soils can generate major instability. Uplift pressures on joints can lead to instability or cracking of the protection component of a levee (CIRIA, 2013).

Furthermore, it is well known that high water levels against a levee for a long period may cause the saturation of the dyke and subsequent structure collapse. Seepage flow can cause changes in the pore water pressure, leading to internal erosion and impacting the stability of the embankment (Staiano et al., 2001; Fox et al., 2006; Vorogushyn et al., 2009; Nardi et al., 2012).

As reported in Nagy and Tóth (2005), due to the continuous heightening of the levees, the type of failure has been changed. In the earlier period of the history of flood protection, the main danger and cause of damages was the overtopping of the river dikes, which was followed by the complete erosion of the dike body itself. The heightening of the dikes led to growing exposure to the foundation soil, supporting the development of hydraulic soil failure, boils, and piping, while the growing duration of floods raised the risk of dike saturation.

Most levee collapses had a common failure mechanism of internal erosion without overtopping. Examples of such failures include the levees of the main rivers in Hungary, such as Tisza or Körösök. These occurrences demand a reassessment of the risk linked to inundation scenarios, as the likelihood of levee failure resulting from its collapse may be higher than overtopping (Nagy and Tóth, 2005; Nagy, 2006). It is worth noting that overtopping may also cause levee collapse.

This study aims to examine the vulnerability of earthen levees to through-seepage, focusing on the time scales associated with soil saturation and peak flood duration processes. The analysis uses the equation for seepage flow proposed by Marchi (1961), as applied by Camici et al. (2015). The equation estimates the critical conditions of levees, considering the soil properties of the levee and the flood hydrograph. This study investigates the effect of the main parameters, such as void ratio, hydraulic conductivity of the levee body, and the depth of the groundwater table level. The results are used in this context to analyze the range of seepage in the Kőrös region in Hungary.

2. Applied analytical model

Marchi's methods for assessing the stability of earthen levees involve a comprehensive analytical approach, primarily applied under the assumption of a steady-state condition with a constant water level in the river for an extended period. This method is particularly applicable when the aquifer thickness below the levee surpasses the water depth in the river. The analytical model considers the levee and its foundation as a uniform layer with consistent properties, assuming homogenous and isotropic geotechnical characteristics. The critical condition arises when the phreatic line reaches the landside slope of the levee cross-section, indicating susceptibility to internal erosion mechanisms like piping, which could lead to a breach in the levee system.

The model combines continuity and Darcy's equations, incorporating several simplifications and assumptions. These include the following:

- neglecting the capillarity fringe,
- Dupuit's hypothesis holds,
- simulating seepage as a plane flow,
- considering a small seepage depth in comparison to the aquifer thickness,
- the levee soil on the riverside slope and under the river water level is not included in the spatial domain.

Despite its theoretical approach, the model may not fully align with real scenarios, as seepage initially fills the soil strata closest to the riverside.

The level of the undisturbed water table is taken as the downstream boundary condition, which is asymptotically reached by the phreatic line at a theoretical 'infinite' distance from the riverside slope. The spatial domain of resolution starts from the vertical plane passing through the intersection between the imposed river water level and the riverside slope (point P4 in Fig. 2): this may not be fully consistent with real situations since seepage first the soil strata nearest to the riverside.

The sketch in Fig. 2 depicts the schematization of the levee geometry and the variables that are relevant to the application of the model. In particular, the following quantities are referred to as the x–y axes centered in P3:

- h_0 = flood level of the river,
- $y_{thalweg}$ = level of the river thalweg,
- H_{LR} = height of levee at the riverside,
- H_{RF} = level of the undisturbed water table,
- h = elevation of the phreatic line,
- x_{in} = value of the horizontal coordinate x that defines the vertical boundary of the spatial domain

By taking into account a schematic rectangular flood hydrograph characterized by the duration of the flood, T, and the flood level, h_0, Marchi proposed a linearised analytical solution that was further simplified for the case of a deep phreatic aquifer (that is when $H_f > L$, with L = horizontal distance between P6 and x_{in} and H_f = thickness of the aquifer). It can be described by Eq. (1)

$$\frac{h(x)+H_{RF}}{h_0+H_{RF}} = \frac{2}{\pi} arctg \frac{k \cdot T}{n \cdot (x-x_{in})} \quad (1)$$

where

- k = hydraulic conductivity of the levee's material,
- n = porosity of the levee's material,

and Eq. (1) is valid for $x>x_{in}$ and $-H_{RF}<y<H_{LR}$

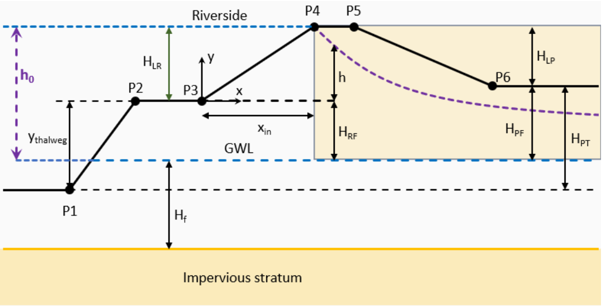

Figure 2. Parameters used in applying Marchi's model (Michelazzo et al., 2018).

The method provides an analytical expression for the phreatic line, considering the seepage front forced by the river water level. The model relies on various hydrological parameters like flood level, river thalweg, levee height, undisturbed water table level, and spatial domain boundary.

A vulnerability index, i_{seep} for the seepage mechanism can be determined as the ratio $\Delta T/T_{CR}$ where ΔT is the hydrological time scale for the duration of river flood level and T_{CR} is the critical time describing the levee resistance time when the phreatic line intersects the landside slope of the levee.

The critical time is directly derived from Eq. (2) by considering the position of the undisturbed water level.

$$T_{CR} = \tan\left(\frac{\pi}{2} \cdot \frac{H_{PF}}{h_0+H_{RF}}\right) \cdot \frac{n \cdot L}{k} \quad (2)$$

where H_{PF} is the elevation of the landside over the undisturbed water table.

The hydrological time scale ΔT can generally be referred to as the duration of the flood levels around the peak for a given hydrological scenario. In the present methodology, ΔT is defined as the duration of water levels above 90% of the maximum level of the hydrograph. The applied classification of the vulnerability index is given in Table 1.

Table 1. Classification of vulnerability

i_{seep}==$\Delta T/T_{cr}$	**Vulnerability class**
< 0.5	Low
0.5 - 1.0	Medium
≥ 1.0	High

High values of the vulnerability index i_{seep} are associated with high values of the ratio $\Delta T/T_{CR}$. It means that the phreatic line intersects the levee body within a shorter time period than the duration of the flood hydrograph.

3. Geology of the study area

Europe's largest inter-mountain basin is the Pannonian Basin, situated in Central Europe and bordered by the Alps, Carpathians, and Dinarides. The Danube River, the primary outflow, is connected to the Black Sea only through a narrow opening in Romania. The study area, the Körös sub-basin, located in the southeastern region of the Pannonian Basin, currently covers around 1600 km^2. Its average height is 84-85 m above sea level, representing one of the lowest parts of the Pannonian Basin. The main rivers of the area include the Berettyó, the Sebes-, Fekete- and Fehér-Körös rivers (see Fig. 3). These rivers have a transverse pattern, running roughly from east to west. They originate from the Apuseni Mountains and transport sediment to the Pannonian Basin in the west. After the confluence of the Fekete- and Fehér-Körös rivers, it is called Kettős-Körös. The lengths of these four transverse rivers are quite similar. However, there are differences in the size, geology and morphology of their catchment areas in the Apuseni Mountains in Romania, which result in characteristic differences in stream gradients. Of these four rivers, the Fekete- and Fehér–Körös coming from the southeast have the highest gradients in their mountain sections.

Figure 3. Location of Körös sub-basin.

The formation of the Pannonian Basin started in the Early-Middle Miocene by back-arc style rifting and coeval with the significant stages of thrusting of the Carpathian belt. Following the Middle Miocene rifting, characterized by two independent extensional phases, a post-rift thermal subsidence occurred during the Late Miocene-Pliocene (Horváth, 1993; Horváth and Cloetingh, 1996). The Pannonian Lake covered the subsided basin, which was in contact with the former Paratethys up to the end of the Badenian. After the complete isolation of the Pannonian Lake from the marine environment, it was filled up by prograded delta systems from the northwest and northeast (Bérczi and Phillips, 1985; Pogácsás et al., 1988). Therefore, the Upper Miocene-Pliocene sequence represents a time-transgressive facies change from offshore basin sediment through basin slope and delta slope to delta front and delta plain sediments, passing up into the alluvial facies, which represent the latest stage of basin fill (Juhász, 1992).

The latest phase of the multistorey development of the Pannninian Basin comprises a still active basin inversion, characterized by NW-SE and N-S compression, which resulted in significant uplift of the marginal parts and local subsidence of the basin center during Quaternary (Csontos et al., 1992; Horváth and Tari, 1999). As a result of this varied morphology, the main rivers transported sediments from the northwest, north, northeast, and east mountain regions towards the central part of the Pannonian Basin. The uninterrupted subsidence of the Körös sub-basin, investigated here, was one of the largest subsiding areas, represented by a 400-500 m thick continuous Pleistocene fluvial record. The Körös sub-basin is bounded north and south by ENE-WSW transtensional faults and an NNE-SSW fault on the cast (Rónai, 1985).

The fluvial deposits of the Körös sub-basin are composed of fine-grained sediments, predominantly silt and clay with minor fine-grained sands, deposited from rivers from the Apesuni Mountains in Romania and the Carpathians (Rónai, 1985). Quaternary transport directions and source areas of the Pleistocene fluvial sediments have been mostly modeled based on the mineralogical composition of sands and silts and the basis of the position of alluvial fans. Previous large-scale studies supposed that the Körös and Berettyó rivers, and their precursors, deposited their sediment load over the area of the Körös sub-basin, changing their flow pattern over the area through time and space, as also did the precursor of the Tisza River. However, the variations in transport directions have not been reconstructed in detail. The relationship between the uplift history of the hinterland area and its influence on the river course pattern has also not been studied (Borsy, 1989).

Over the past 100 years, the Fehér-, Fekete-, and Kettős-Körös rivers, which flow into the Tisza River, have had a stormy history in terms of flood protection. The flood levels have been rising intensely, with a high frequency of severe flooding. In the 20th century, out of 17 significant floodings in this watershed system, 10 breaches occurred (see Fig. 4) (Szlávik et al., 1999).

Figure 4. Breach at the Kettős-Körös in 1980.

Because of the repeated flood events mentioned above, the height increase of artificial levees with time is shown in Fig. 5. The levee height ranges from 5 to 7 meters. The earth structure's material is primarily clayey and silty (Sheishah et al., 2023).

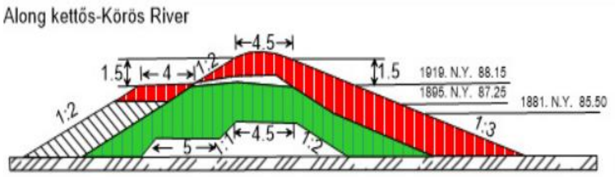

Figure 5. Evolution of levee along Kettős-Körös.

4. Results

A geotechnical investigation campaign was conducted to obtain insight into the subsoil's layering and physical mechanical characteristics. Both undisturbed and disturbed samples were taken during the geotechnical drilling and tested in a laboratory. The foundation soil consists of medium and high-plasticity clay. The levee body contains silt and clay with varying sand content.

The levee was built in four stages. The first part was built around 1880 with high-plasticity clay. The second stage was built around 1920 because of concerns about levee safety. This section contains mainly silty material. In the past 50 years, the levee was raised further and widened. The waterside slope was flattened to 1:3, the landside slope developed to 1:2, and a landside berm was constructed. The additional part of the levee contains mainly low-plasticity clay with varying sand content. The actual height of the levee is 5.2 m.

The groundwater elevation follows the river elevation changes and is close to the surface. As a result, the soils in the foundation are almost always saturated.

Fig. 6 shows the plasticity chart. It suggests that the levee has varying materials, with a plasticity index from I_P=11% to I_P=42%.

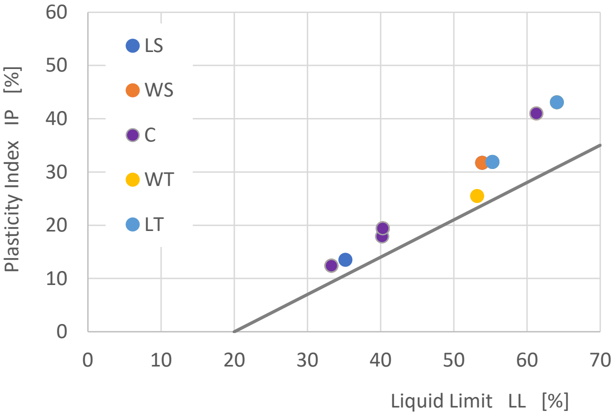

Figure 6. Plasticity chart.

Fig. 7 shows the estimated phreatic lines for two flood durations: T = 20 and T = 100 hours. The lines start at the levee's crest on the riverside and gradually decrease their elevation until asymptotically reaching the undisturbed water table level. For a shorter flood period, the phreatic line intersects the levee's landside slope at the levee toe. For longer flood durations, the position of the phreatic appears at higher elevations. The parameters applied are k=0,8 m/day, n=0,3, and the groundwater table level is 1.0 m below the surface elevation on the riverside.

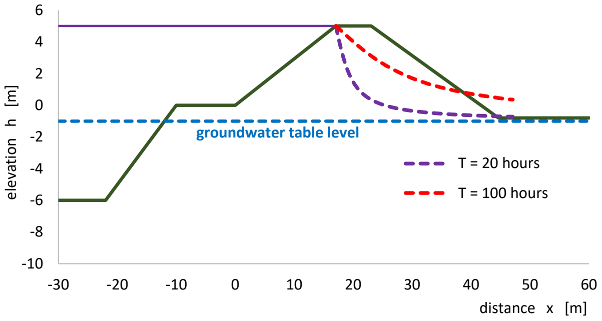

Figure 7. Phreatic lines for different flood durations, T.

The seepage phenomenon is strongly dependent on the geotechnical properties of the soil, mainly from the permeability and porosity of the material. The effect of the different soil types was investigated by conducting a sensitivity analysis.

For the analysis, the hydraulic conductivity varied between k=4,3 m/day and k=0,043 m/day, representing the different sand content. The higher the value of permeability, the higher the sand content.

Fig. 8 shows the relationship between critical time (T_{CR}) and hydraulic conductivity, considering different hydraulic head scenarios (h_0). The porosity of the levee material is assumed to be n=0,3. As expected, the lower the permeability, the longer the critical time. Increasing the hydraulic head causes the reduction of the critical time.

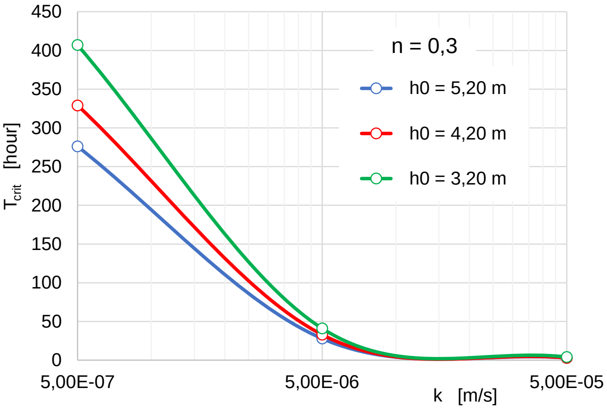

Figure 8. hydraulic conductivity vs. critical time.

Fig. 9 shows the relationship between the critical time (T_{CR}) and the hydraulic head, considering different scenarios of the porosity. The permeability of the levee material is assumed to be k=0,43 m/day and the porosity has a small effect on the critical time.

Fig. 10 shows the effect of the groundwater table level. The proposed hydraulic conductivity of the earthen levee is k=0,43 m/day, and the porosity is n=0,35. The results highlight the strong effect of the groundwater table elevation. The deeper the groundwater table level, the higher the critical time.

The following analysis demonstrates the versatility and vulnerability of the levee. Considering the permeability, k=0,43 m/day, the average void ratio, e=0,6, the high groundwater table level, and different hydrological time scale ΔT, the calculated vulnerability indexes are summarized in Table 2 referring to water level h_0=4,8 m on the riverside.

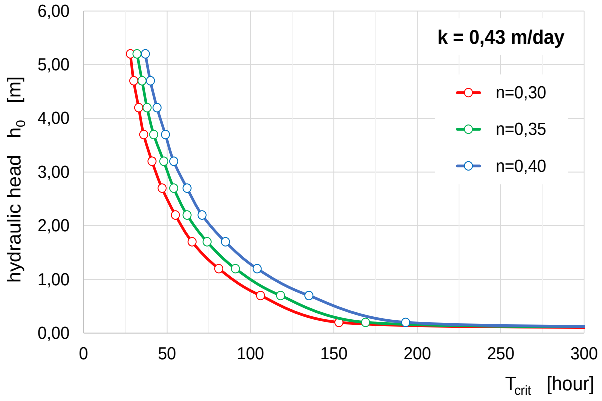

Figure 9. Hydraulic head vs critical time.

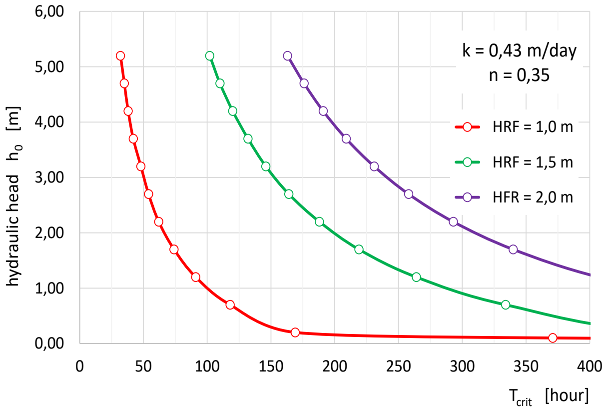

Figure 10. Effect of the groundwater table level.

Results indicate that the investigated section in the Körös sub-basin becomes critical if the duration of flood level exceeds ΔT≈30 days.

Table 2. Vulnerability classification

ΔT [days]	**10**	**25**	**40**	**65**	**100**
i_{seep}	0,29	0,74	1,47	2,21	2,94

5. Conclusions

This paper presents a methodology for assessing the susceptibility of earthen levees to through-seepage phenomena, focusing on the critical time scale associated with seepage conditions and the duration of the flood water level. The reference condition occurs when the phreatic line appears on the landside of the levee slope, indicating the presence of internal erosion mechanisms. If the critical period is shorter than the hydrological time scale, the levee is categorized as vulnerable to seepage, which can result in structural failure and levee body breaching.

The study is applied to the Körös sub-basin, where rising water levels have been observed in recent years. The analysis reveals that levee geometry along the Kettős-Körös river, characterized by the registered critical time, shows higher vulnerability to lower water levels associated with longer flood water levels.

Integrating the analysis with hazard maps focusing on overtopping and historical data on levee breaches offers insights for flood-risk management, streamlining maintenance, and emergency response.

Acknowledgements

The research presented in the article was carried out within the framework of the Széchenyi Plan Plus program with the support of the RRF 2.3.1 21 2022 00008 project.

References

Bérczi, I., Phillips, R. L., "Processes and depositional environments within deltaic-lacustrine sediments, Pannonian Basin, Southeast Hungary", Geophysical Transactions, 31. 55-74, 1985.

Borsy, Z., “Az Alföld hordalékkúpjainak negyedidőszaki fejlődéstörténete” Földrajzi Értesítő, 38. 211-224, 1989. (in Hungarian)

Brandl, H. and Szabo, M., "Hydraulic failure by underseepage of dykes and levees." In: XVI DECGE 2018 Proceedings of the 16th Danube - European Conference on Geotechnical Engineering, Macedonia, 2018, Volume 2, Issue 2-3, pp. 19–38. https://doi.org/10.1002/cepa.660

Camici, S., Barbetta, S., Moramarco, T., “Levee body vulnerability to seepage: the case study of the levee failure along the Foenna stream on 1st January 2006 (central Italy)”, Journal of Flood Risk Management, Volume10, Issue3, pp. 314-325, 2015. https://doi.org/10.1111/jfr3.12137

CRED, “Review of Disaster Events. Supplementary Information”, Available at: https://reliefweb.int/report/world/2018-review-disaster-events-supplementary-information, accessed: 15/January/2024.

CIRIA, Ministry of Ecology, USACE, “The international levee handbook”, CIRIA, London, 2013. ISBN: 978-0-86017-734-0

Csontos, L., Nagymarosy, A., Horváth, F., Kovác, M., “Tertiary evolution of the Intra-Carpathian area: A model”, Tectonophysics, Volume 208, Issues 1–3, pp. 221-241, 1992. https://doi.org/10.1016/0040-1951(92)90346-8

Fox, G. A., Wilson, G. V., Periketi, R. K., Cullum, R. F., “Sediment transport model for seepage erosion of streambank sediment”, Journal of Hydrologic Engineering, Volume 11, no. 6, pp. 603–611, 2006. https://doi.org/10.1061/(ASCE)1084-0699(2006)11:6(603

Garrote, J., Bernal, N., Díez-Herrero, A., Martins, L.R., Bodoque, J.M., “Civil engineering works versus self-protection measures for the mitigation of floods economic risk. A case study from a new classification criterion for cost-benefit analysis”, International Journal of Disaster Risk Reduction, Volume 37, no. 101157, 2019. https://doi.org/10.1016/j.ijdrr.2019.101157

Horváth, F., “Towards a mechanical model for the formation of the Pannonian basin”, Tectonophysics, Volume 226, Issues 1–4, pp. 333-357, 1993. https://doi.org/10.1016/0040-1951(93)90126-5

Horváth, F., Cloetingh, S., “Stress-induced late-stage subsidence anomalies in the Pannonian basin”, Tectonophysics, Volume 266, Issues 1–4, pp. 287-300, 1996. https://doi.org/10.1016/S0040-1951(96)00194-1

Horváth, F., Tari, G. “IBS Pannonian Basin project: a review of the main results and their bearings on hydrocarbon exploration.” In: Durand, B., Jolivet, L., Horváth, F & Sérrane, M. (eds) The Mediterranean Basins: Teriary Extension Within the Alpine Oregon. Geological Society, London, Special Publications, 156. 195-213, 1999. https://doi.org/10.1144/GSL.SP.1999.156.01.11

Juhász, Gy. “A pannóniai s.l. formációk térképezése az Alföldön: elterjedés, fácies és üledékes környezetek”, Földtani Közlöny, 122. pp. 133-165, 1992. (in Hungarian)

Michelazzo, G., Paris, E., Solari, L., “On the vulnerability of river levees induced by seepage”, Journal of Flood Risk Management, Volume 11, Issue S2, pp. S677-S686, 2018. https://doi.org/10.1111/jfr3.12261

Morris M., Dyer, M. and Smith, P. “Management of flood embankments. A good practice review.” Defra/Environment Agency, 2007.

Nagy, L., “Estimating Dike Breach Length from Historical Data” Period. Polytech. Civ. Eng. 50, pp. 125–139, 2006.

Nagy, L., Tòth, S., “Detailed Technical Report on the collation and analysis of dike breach data with regards to formation process and location factors”, Technical Report, H-EURAqua Ltd., Hungary, 2005.

Nardi, L., Rinaldi, M., Solari, L., “An experimental investigation on mass failures occurring in a riverbank composed of sandy gravel”, Geomorphology, Volumes 163–164, pp. 56-69, 2012. https://doi.org/10.1016/j.geomorph.2011.08.006

Ozkan, S., “Analytical study on flood induced seepage under river levees”, Doctoral Dissertation, Louisiana State University, 2003. Available at: https://repository.lsu.edu/gradschool_dissertations/2342, accessed: 20/December/2023.

Pogacsás, G., Lakatos, L., Ujszászi, K., Vakarcs, G., Várkonyi, L., Várnai, P., Révesz, I., “Seizmic facies, electro facies and Neogene sequence chronology of the Pannonian basin”, Acta Geologica Hungarica 31(3-4), pp. 175-207, 1988.

Rónai, A. “Az Alföld negyedidőszaki földtana”, Geologica Hungarica series, Geologica, 21. 1985. (in Hungarian)

Sheishah, D., Kiss, T., Borza, T., Fiala, K., Kozák, P., Abdelsamei, E., Tóth, Cs., Grenerczy, Gy., Dávid, G. P., Sipos, Gy., “Mapping subsurface defects and surface deformation along the artificial levee of the Lower Tisza River, Hungary”, Natural Hazards, 117, pp. 1647–1671, 2023. https://doi.org/10.1007/s11069-023-05922-1

Staiano, T., Rinaldi, M., Paris, E., “Seepage and stability analysis of embankments during flood events”, In: XXIX IAHR Congress Proceedings, Beijing, China, pp.16-21, 2001.

Szlávik, L., Galbáts, Z., Kiss, A., Kisházi, P. K., Rátky, I., “A Fehér-, Fekete- és Kettős-Körös árvizei, árvízvédelmi rendszere és a Kisdelta szükségtározó”, Vízügyi Közlemények, 81: 4, pp. 543-614, 1999. (in Hungarian)

Vorogushyn, S., Merz, B., Apel, H., “Development of dike fragility curves for piping and micro-instability breach mechanisms”, Natural Hazards and Earth System Sciences, Volume 9, issue 4, pp. 1383–1401, 2009. https://doi.org/10.5194/nhess-9-1383-2009