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Mapping and Evaluating the Condition of Artificial Levees

PhD Dissertation

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1. Introduction

Floods are among the most widespread types of natural hazards, since by almost half of the catastrophes in the last decade were related to floods. One of the most dangerous threat related to floods is the loss of human lives, but they also harm economic and social infrastructure (Mezősi, 2022).

Artificial levees, i.e.: manmade linear earthworks along rivers, are ultimately important items of flood prevention and flood risk reduction. Thus, knowing their condition is essential for successful flood protection. Most of the levee system along the Tisza was originally constructed in a relatively short period during the 19th century. However, the first levees failed several times and were overtopped by the river (e.g. 1879 flood of Szeged). Consequently, the height and size of levees was continuously increased over time, usually after significant and destructive flood events. This resulted an onion-like complex earth structure with spatially variable composition.

In the present study, we aimed to combine the strength of different geophysical techniques, such as Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) as well as levelling data, real-time kinematic GPS (RTK-GPS) data, and Persistent Scatterer Synthetic Aperture Radar (PSI) on levee sections along the lower sections of the Tisza and Maros Rivers in order to test the potential of an integrated approach in levee health assessment and to determine the limitations of the applied methods.

2. Study area and methods

The study area is situated on the left bank of River Tisza and the left bank of River Maros in the southern part of Hungary. A 48 km levee section was chosen for geophysical surveys and drillings (**Fig. 1**). lkm stands for levee kilometre.

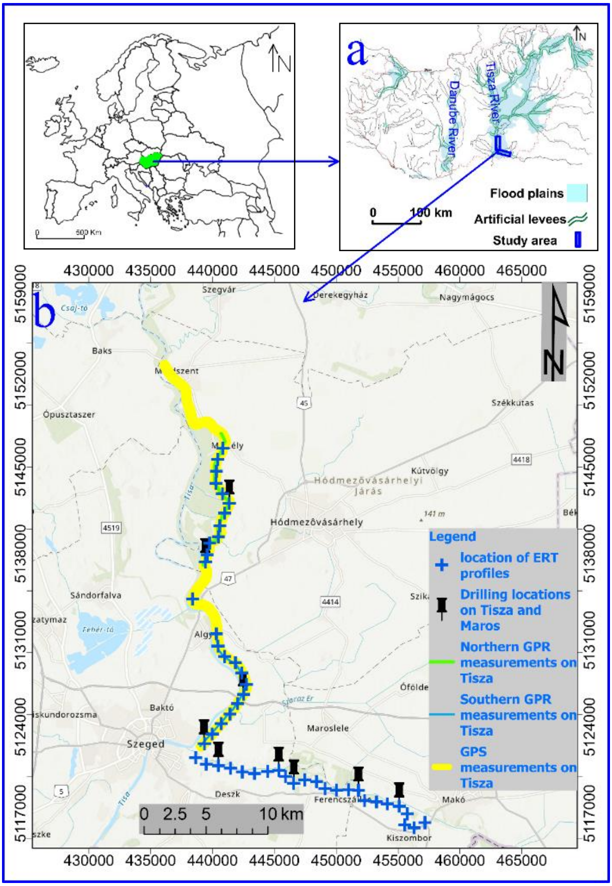

Fig. 1 A) Location map with potential floodplains and artificial levees in Hungary (modified after OVF 2014), and B) the study area showing the places of RTK-GPS measurements as a yellow line and levee sections surveyed by GPR and ERT and drilling locations

2.1 Elevation change

GPS measurements were performed at every 200 m on the crown and foot along the Tisza levee section between 12.5 and 42.0 lkm, using a TopCon Hyper Pro device in 2017 and 2018 **Fig. 1**. Concerning the levee crown, the baseline elevation data was derived from differential levelling made by the Lower Tisza Water Directorate in 1976. Elevation changes were compared to Persistent Scatterer Synthetic Aperture Radar (PSI) data as well as there can be are several factors in the mm to cm range affecting levee height besides geologically driven subsidence or uplift.

2.2 ERT

ERT data was collected using a GeoTom MK8E100 apparatus with a multi-electrode system (50 electrodes). A total of 109 ERT profiles were collected at two levee sections: the first section was at the left bank of River Tisza from 13-1km to 42-lkm (7 km section from 24 lkm to 31 lkm was not investigated because the levee crown was paved), and the second section was at the left bank of River Maros from 1-lkm to 24-lkm **Fig. 1**. At each levee km, the first profile was measured longitudinally on the levee crown and the second profile was measured transversely covering the levee crown and both slopes on the river and protected sides of the levee.

2.3 GPR

The GPR survey was conducted using SIR 3000 control unit (Geophysical Survey Systems Inc.) attached to a 200 MHz centre frequency antenna in the survey wheel mode. The data was collected on the left bank of the Tisza River. It is subdivided into two zones termed as southern levee zone (12.6 lkm - 23.9 lkm) and the Northern levee zone (31.2 lkm- 43.10 lkm) as these zones are separated by a 7 km long asphalted levee section. Measurements were performed on the levee crown and at some places at the levee foot as well. A total of 282 GPR profiles were collected. Regarding the southern zone 162 GPR Profiles were measured: 114 GPR profiles were conducted on the levee crown and 48 GPR profiles were conducted on the levee foot. Regarding the northern zone, 120 GPR profiles were measured on the levee crown **Fig. 1**. All the GPR profiles were obtained successively, which means that the endpoint of one profile was the starting point of the next profile. Each GPR profile had a 100 m length

To study the application of different centre frequency antennas and their applicability for levee studies, at some sections GPR surveys were also conducted by applying another system (IDS) with a different centre frequencies (80 MHz).

2.4 Sedimentological data

In order to correctly interpret and validate ERT surveys, 19 boreholes were drilled at definite locations on the Tisza and Maros levees **Fig. 1**. Two boreholes were made at each mentioned site: the first one was on the riverside edge and the second one was on the protected side slope of the levee. Drilling was carried out using an Eijkelkamp drilling system with a 5 cm diameter drilling head. A total of 457 samples were collected and different parameters were measured. Grain-size (D50) was performed with a Fritsch Analysette 22 laser analyser, water content (W) was measured from the calculations of the difference between wet samples' weight and dried samples' weight, saturated hydraulic conductivity (K) was measured by Penetrometer, bulk density (ρ) was obtained from the weight of the dry samples divided by the volume of the soil sampling cylinder, porosity (φ) was calculated from the bulk density of the material by knowing the particle density of the material (2.65 g/cm^3).

2.5 Methodology of evaluating levee health

The risk potential at every km of the investigated levee section along the Tisza (12.6 lkm – 43.1lkm) was assessed by combining the different data we obtained. The analysis was carried out by calculating at every km of the entire investigated area: 1) the mean elevation decrease, 2) the mean penetration depth of GPR signals, 3) the mean number of GPR anomalies and 4) the dominance of fine silt units in the levee core over medium silt. These values were compared to values calculated for 1 km sections. At each 1 km section, the values of the above four parameters were compared to the mean of the entire section. If the 1 km value was higher than section average, it received a score of "2" referring to a higher level of levee health than average.

On the other hand, if the 1 km value was below the section mean, it received a score of "1", referring to a lower level of levee health than average.

2.6 Inventory of historical flood phenomena

Based on the 50-year long record of the Lower Tisza Water Directorate, six major types of flood phenomena have been identified along the studied levee section **Fig. 2**. Based on an overall review of recordings, seepage and piping were identified as the most frequently occurring phenomena. These affect the upper part of the levee body, mostly within the estimated range of GPR penetration depth. The frequency diagram of seepage and piping phenomena were compared to the spatial frequency of anomalies, identified using GPR profiles.

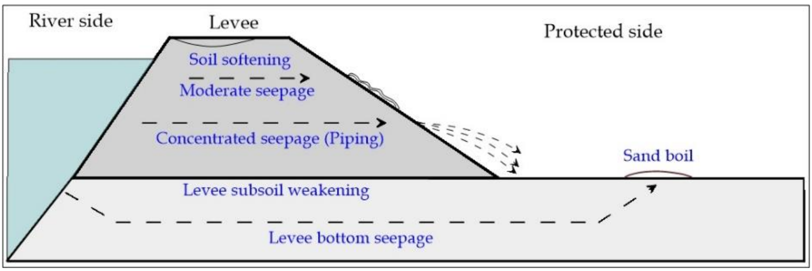

Fig. 2 Six types of flood phenomena identified by the Lower Tisza Water Directorate along the investigated levee section

3. Results and theses

3.1 Mapping the structure and composition of the investigated levees

Thesis 1: With the help of sedimentological data, ERT could provide information about the structures and changes of the materials along the investigated levee sections. In the case of the Tisza levee section and by following up the longitudinal profiles measured on the Tisza levee crown, it is noticed that two materials, medium and fine silt, are the main components of the levee core **Fig. 3b**. Regarding the transverse profiles measured on the Tisza levee, both river and protected sides are composed of fine and medium silts, as shown in **Fig. 3a and c**.

Thesis 2: In contrast to the investigated Tisza levee section, the investigated Maros levee section is more complicated and shows more variety in the materials from fine silt to coarse sand (fine silt, medium silt, coarse silt, fine sand, medium sand, and coarse sand) and at some parts the alternation of fine and medium silt could be noticed. In general, the longitudinal profiles measured on the crown of Maros levee showed that the levee core is composed of medium and fine silts except for three sections at 8-lkm, 16-lkm, and 22-lkm showing coarse silt, fine and medium sand as well **Fig. 4b**. Regarding the transverse profiles measured on Maros levee, 17 levee km sections out of the whole investigated sections (24 lkm long) show a sand backfill in the protected side. These sections are from 2-lkm to 9-lkm, 13-lkm to 19-lkm, at 22-lkm, and 24-lkm, as shown in **Fig. 4a and c**. The rest of the sections show silty materials. The riverside slope of Maros levee is composed of silty materials.

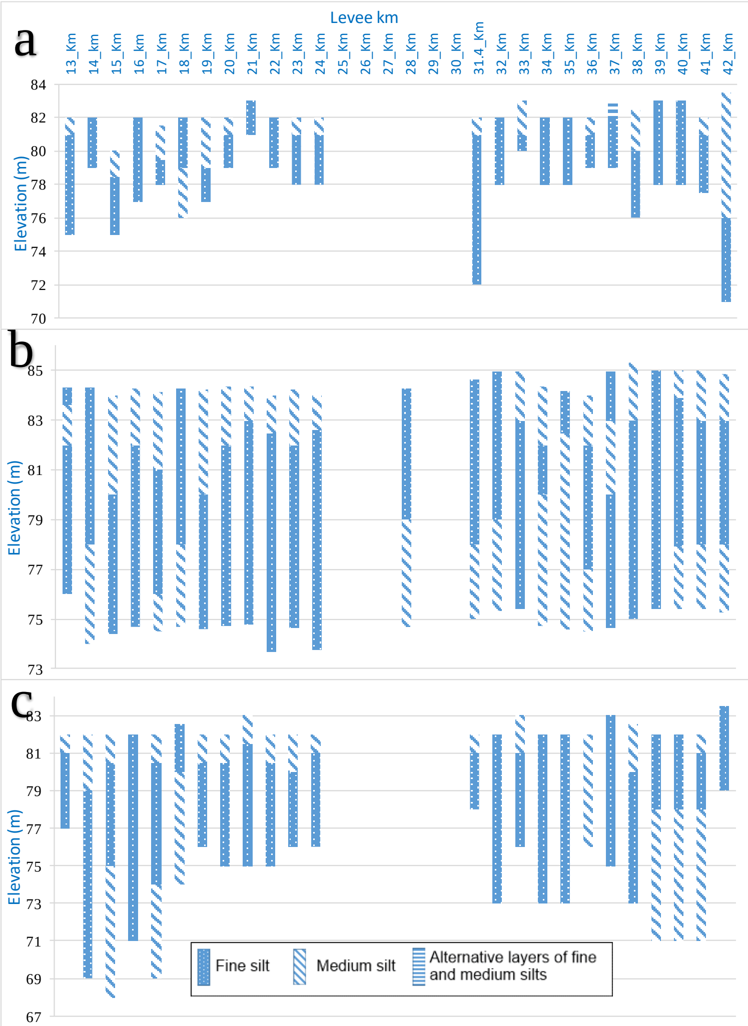

Fig. 3 Mapping the composition of the investigated Tisza levee section; A) along the riverside, B) along the levee crown, and C) along the protected side

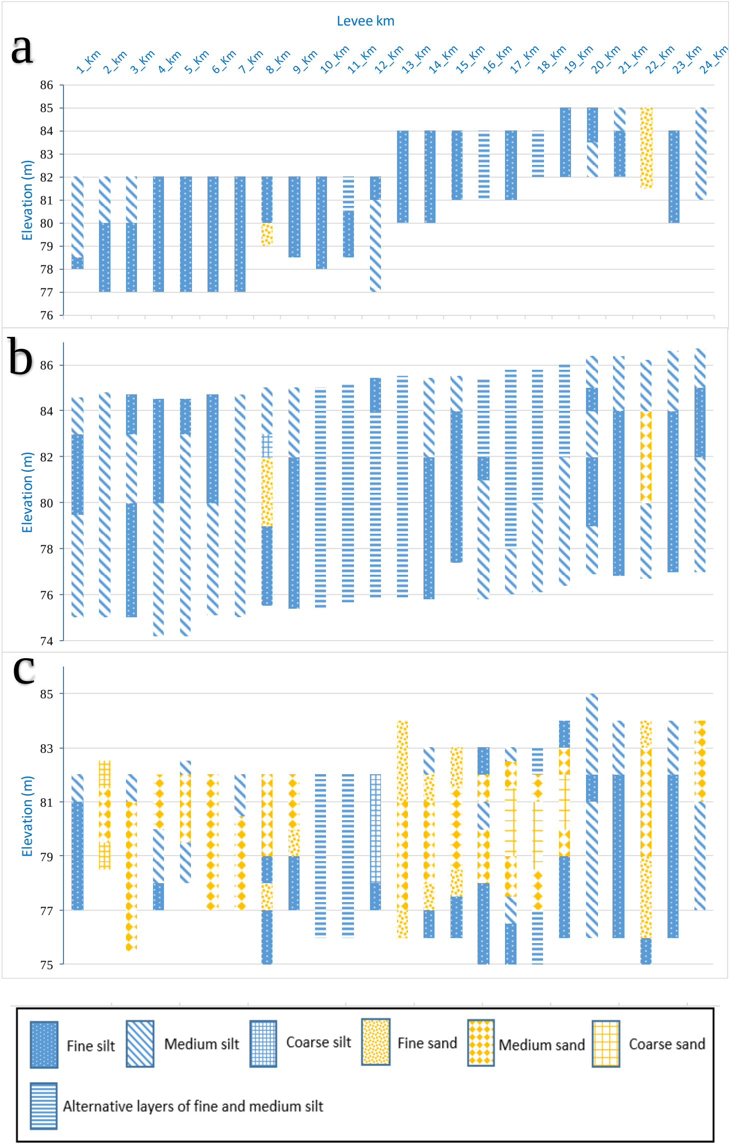

Fig. 4 Mapping the composition of the investigated Maros levee section; A) along the riverside, B) along the levee crown, and C) along the protected side

3.2. Relationship between resistivity and other physical parameters

Thesis 3: Based on the results obtained by drilling and sedimentological analysis, the parameters affecting resistivity the most are water content and grain size, however if all samples are considered together, a relatively weak correlation can be seen between these and resistivity. In case samples classified based on their water content, a remarkable good relationship can be found between grain size and resistivity values. The correlations among resistivity and the other parameters showed high degree of significance and it was positive in case of D50, K, φ and negative in case of W and ρ. This underlines the importance of orienteering drillings during ERT surveys to help the more precise identification of levee composition. In other words, with an integrated approach it is possible to map levee structures and composition on large sections using ERT.

3.3. Elevation change of levees

Thesis 4: In general, the elevation values were clearly lower in 2017 than in 1976. The annual rate of subsidence for these sections is 1.3 mm/yr. To investigate in more detail, the spatial variation of changes, elevation differences were also evaluated by applying a moving average analysis (1 km window at 200 m steps). Even in terms of unpaved sections height change is not uniform, i.e. some parts are affected more by elevation decrease, such as the levee section between 32 and 41 lkm (-16 cm on average), or between 13 and 17 lkm (-29 cm on average) **Fig. 5**. Such spatial differences imply that elevation decrease cannot simply be explained by compaction and/or mass-related subsidence, which should affect the entire section in a similar way but there can be other forces leading to non-uniform subsidence.

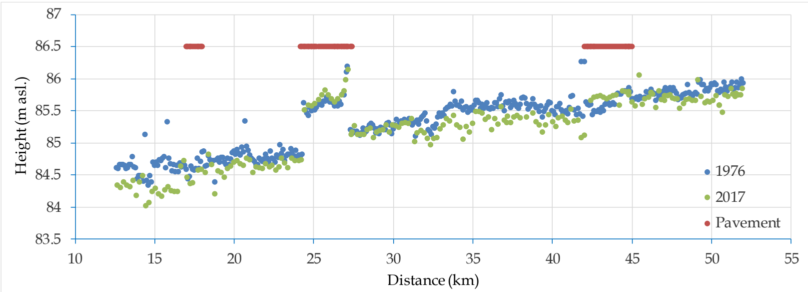

Fig. 5 Elevation data of the levee crown in 1976 (blue points) and 2017 (green points). Red lines mark sections where the levee crown is paved

The spatially uneven subsidence in the area is also reinforced by the PSI data, In the investigated 18-year period (1992-2010) surface deformation velocities ranged between +0.5 and -5.0 mm/yr, thus the average subsidence rate along the section investigated (12.5-39.0 lkm) was 1.9 mm/year. This value is very close to the rate calculated using levelling and GPS data (1.3 mm/year).

3.4. Identification of GPR anomalies

Thesis 5: After processing the GPR profiles, six types of anomalies were identified, each affecting flood risk differently by modifying the levee structure as illustrated in **Table 1**. The anomalies that can be identified by GPR surveying are: tensile cracks, remarkable change in dielectric permittivity (composition), animal burrows, layer deformation, sudden change in stratification, and finally at the levee foot the presence of plaeo river channels. The mapping of GPR anomalies is restricted to the upper 4 m of the levee.

Table 1: Different anomalies identified during interpretation of 2D-GPR profiles and their evaluation in terms of flood risk.

No.	Legend	Name	Evaluation in terms of flood hazard	No. of GPR profiles affected	%
1		Tensile cracks	Enables piping, leading to levee breach or mass failure Cracks might close when the levee gets wet	87	30
2		Remarkable changes in dielectric permittivity	Enables seepage, leading to mass failure	70	25
3		Animal burrows	Enables piping, leading to levee breach or mass failure	33	12
4		Layer deformation	Results in height decrease, overtopping	6	2
5		Paleo river channel	Enables seepage below the levee, leading to water upwelling and the development of sand boils	5	2
6		Sudden change in stratification (dipping layers)	Enables contour line seepage, leading to mass failure	4	1.5

Thesis 6: GPR results were compared with 2006 and 2010 piping and moderate seepage recordings made along the studied levee section **Fig. 6**. Although, the spatial pattern of km based data of anomalies and flood phenomena do not match completely, the general difference between the southern and northern investigated zones of Tisza levee is obvious. The relationship is particularly clearer if the total number of recordings for a zone is given as a percentage of all recordings. The proportionate value of piping and moderate seepage was 70% and 30% in the southern and northern zones respectively.

Very similar values were obtained when remarkable changes in dielectric permittivity were considered (74% vs. 26%), and a somewhat different, but still comparable distribution was experienced when each type of anomaly were taken into account (78% vs. 22%). Based on the above, the application of GPR has a great potential to survey levee conditions in the shallow zone.

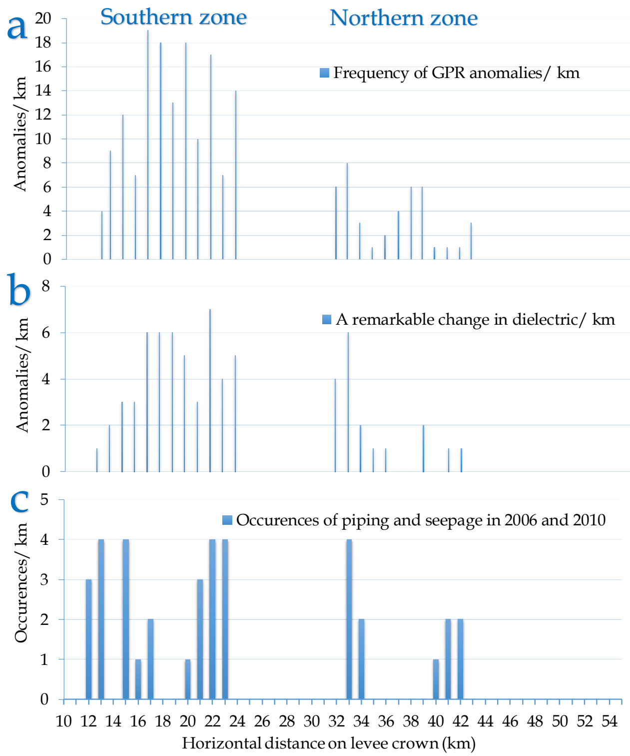

Fig. 6: A) Spatial frequency of anomalies identified from GPR profiles measured on the levee crown each one 1Km, B) a special frequency of a remarkable change in dielectric each 1km section, and C) Occurrence of piping phenomenon) each one Km during two flood periods in 2006 and 2010.

4. Evaluation of levee health

Thesis 7: Concerning the investigated Tisza levee sections the combined results of the levelling data from 1976 and GPS data measured in 2017 were spatially fitted to GPR penetration depth data, the distribution of GPR anomalies detected on the levee crown and the dominance of materials forming the levee core identified on ERT profiles. The risk potential at every km of the investigated levee section was assessed by combining the obtained data . Subsequently, scores of levee health levels were added up, and for each 1 km section, a potential level of levee health value was assigned: scores 4 and 5 meaning very low and low and scores 7 and 8, meaning high and very high risky sections or very high level of levee health potential **(Fig. 7).**

Going from north to south, an increasing trend can be seen in levels of levee health scores **(Fig. 7)**. Very low and low levels of levee health sections are predominant in most of the northern zone except for one lkm section with a medium level of levee health (at 34-lkm). In contrast to the northern zone, in the southern zone, mostly medium levels of levee health sections from 21 lkm to 18 lkm and high levels of levee health sections from 17 lkm to 14 lkm can be identified, and even very high levels of levee health section occur (at 13 lkm), while low levels of levee health sections are restricted only to the first part of this zone at (23 lkm and 22 lkm). Accordingly, the mean level of levee health score in the southern zone is 6.25, while in the northern zone, it is 4.6, referring to the overall worse condition of the southern zone. Consequently, the southern levee zone can be considered more prone to flood phenomena and failure during floods.

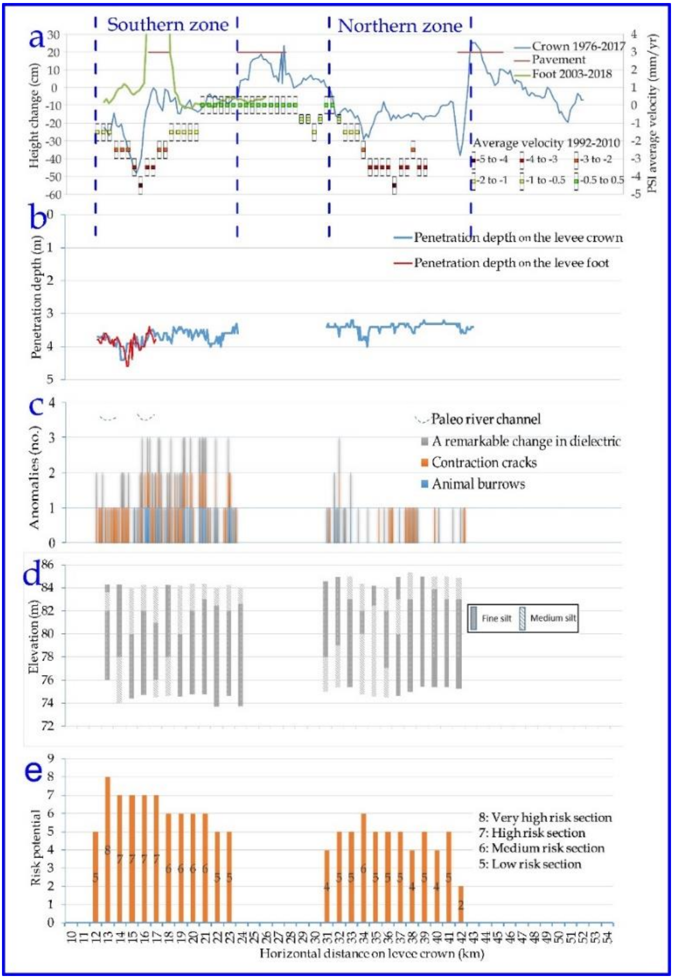

Fig. 7: The spatial distribution of parameters influencing flood risk related to the levee. A) Moving average of elevation change , B) Penetration depth of GPR , C) Anomalies identified on GPR profiles, d) dominant materials of the levee core identified on ERT profiles, and e) risk evaluation for each 1 km section

List of publications during the PhD

- **<u>Sheishah, D.,</u>** Kiss, T., Borza, T., Fiala, K., & Kozák, P. (2023). Mapping subsurface defects and surface deformation along the artificial levee of the Lower Tisza River, Hungary. Natural Hazards, https://doi.org/10.1007/s11069-023-05922-1
- **<u>Sheishah, D</u>**., Sipos, G., Hegyi, A., Kozák, P., Abdelsamei, E., Tóth, C., Onaca, A., & Páll, D. G. (2022). Assessing the Structure and Composition of Artificial Levees Along the Lower Tisza River (Hungary). *Geographica Pannonica*, *26*(3), 258–272. https://doi.org/10.5937/gp26-39474
- **<u>Sheishah, D</u>**., Sipos, G., Barta, K., Abdelsamei, E., Hegyi, A., Onaca, A., & Abbas, A. M. (2023). Comparative evaluation of the material of the artificial levees. *Journal of Environmental Geography*, *16*(1–4), 1–10. https://doi.org/10.14232/jengeo-2023-44452
- Bartyik, T., Floca, C., Pál-Molnár, E., Urdea, P., **<u>Hamed, Diaa</u>**, & Sipos, G. (2021). The Potential Use of Osl Properties of Quartz in Investigating Fluvial Processes on the Catchment of River Mureş, Romania. Journal of Environmental Geography, 14(1-2), 58-67. https://doi.org/10.2478/jengeo-2021-0006
- Rekeczki, Kinga, Dávid Filyó, Adrián Berta, Tamás Bartyik, Mária Wolf, Mária Tóth, **<u>Diaa Sheishah</u>**, and György Sipos. (2021) "A dombói vár tégláinak kormeghatározása termolumineszcens módszerrel." ARCHEOMETRIAI MŰHELY 18, no. 2: 157-174. https://doi.org/10.55023/issn.1786-271X.2021-013
- Boudewijn van Leeuwen, Zalán Tobak, Olivér Balogh, Boglárka Runa, György Sipos, István Fi, **<u>Diaa Sheishah</u>**, Enas Abdelsamei, and Sándor Trenka (2023)."Geoinformatics tools for road quality analysis and mapping" THEORY MEETS PRACTICE IN GIS. p327-335 https://giskonferencia.unideb.hu/arch/GIS_Konf_kotet_2023.pdf

List of conferences that I participated during the PhD

- ***Carpatho-Balkan-Dinaric Conference on Geomorphology*** June 24-27, 2019, Szeged, Hungary: Poster presentation entitled "**Mapping structural defects and subsidence zones along the artificial levees of the Tisza River, Hungary**" http://www.geo.u-szeged.hu/carpatho/
- ***10th Hungarian Geographical Conference***, September 24-25, 2021 Budapest, Hungary: Oral presentation entitled "**Mapping the condition of artificial levees using different methods along the Lower Tisza River, Hungary**" https://mfk2020.elte.hu/en/
- ***GeoMATES'22 International Congress on Geomathematics in Earth- & Environmental Sciences*** 19-21 May 2022 Pécs, Hungary Oral presentation entitled "**Combined geophysical investigations to assess the artificial levee compositions along Tisza and Maros rivers, Hungary**" https://geomates.eu/
- ***Natural Hazards and Climate Change conference*** 23-24 March 2023, Szeged, Hungary Poster presentation entitled "**Comparative evaluation of the material of the artificial levees: a case study along the Tisza and Maros Rivers, Hungary**" https://geosci.u-szeged.hu/gisgeo/rendezvenyek-esemenyek/natural-hazards-and-230215
- ***18th Carpathian Basin Conference For Environmental Science***, 17–19 May 2023 Szeged, Hungary. Oral presentation entitled "**Assessing and Mapping the Structure and Composition of Artificial Levees along the Tisza and Maros Rivers, (Hungary)**" https://geosci.u-szeged.hu/gisgeo/english/18th-carpathian-basin
- ***XIII. International Conference On Transport Sciences*** June 8-9 2023 Győr, Hungary. Oral presentation entitled "Application of GPR in the assessment of aged roads with a complex structure" https://cots.sze.hu/en_GB/2022