

Assessing Levee Stability Under Climate Change: A Case Study of Szigetköz, Ásványráró

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Levees are critical flood protection structures, safeguarding communities and ecosystems from riverine flooding. However, climate change-induced alterations in precipitation patterns, flood magnitudes, and soil stability pose significant challenges to levee performance. This study evaluates the stability and resilience of the Ásványráró levee in the Szigetköz region, northwest Hungary, under projected climate change impacts. The research employs a combination of geotechnical field data and numerical modelling to assess levee behaviour under various stress conditions. Cone Penetration Testing (CPT) was conducted to determine the geotechnical properties of levee foundation soils, providing insights into stratigraphy, permeability, and shear strength. These data were incorporated into Plaxis 2D finite element modelling to simulate flood scenarios, seepage effects, and potential failure mechanisms under different climate projections. Overall, the results showed that climate change significantly increases levee vulnerability through enhanced seepage, deformation, and hydraulic loading. Results indicate that increased flood intensity and prolonged inundation exacerbate levee instability through overtopping, seepage-induced erosion, and slope failure. The findings highlight the necessity for proactive levee reinforcement strategies and adaptive management of levee systems. This study underscores the importance of integrating climate change projections into levee design and maintenance plans, providing a framework for policymakers and engineers to enhance flood resilience in vulnerable regions. By adopting advanced geotechnical assessments and numerical simulations, the research contributes to the development of more robust and climate-adaptive flood defence systems.

1. Introduction

Riverine and coastal populations, agriculture, and infrastructure have long relied on levees for flood protection. These structures are the main flood defence, but climate change is straining them. Higher temperatures changed precipitation patterns, and more intense weather increase flood risks and challenge levee resilience (Vahedifard et al., 2020). Historical data-designed levees may fail under current and future conditions, causing overtopping, piping, or slope failures with serious human, economic, and environmental repercussions. Civil and geotechnical engineers now evaluate levee performance under changing climates. A prominent case study is northwest Hungary's Szigetköz area, bordering Slovakia on the Danube. The Ásványráró village is protected by earthen levees on this intricate floodplain. Climate change is increasing flood frequency and intensity in the region, which was vulnerable to floods in 2002, 2013, and 2021. Multiple seepage pathways, pore pressure changes, and soil saturation increase structural vulnerability in levees due to the Danube's complex hydraulic network of side arms and distributaries. Traditional designs assume stable hydrological patterns, but climate change undermines this. In Ásványráró, questions arise about the durability of older levees during expected higher flood levels, lengthier flood episodes, and increased rainfall. Internal erosion, plumbing, and instability still pose risks. Despite prior floods revealing shortcomings, little research has coupled field-based soil characterization with numerical modelling to estimate levee resilience under future climatic stresses. To fill this gap, our study models a levee section in Ásványráró using site-specific CPT data and PLAXIS 2D. Flood and

rainfall-induced stresses, groundwater flow, pore pressure, and displacement are simulated to uncover failure processes and evaluate climate-resilient design mitigation strategies.

The objectives include modelling levee cross-sections with CPT-derived soil parameters, multiple flood durations and rainfall infiltration simulations, and assessing displacement, hydraulic gradient, groundwater flow, test domain and boundary condition combinations for seepage modelling accuracy, cutoff walls. Toe drainage, and longer embankments are being tested. The study examines; Future climatic scenario levee response to longer flooding and rains; Key loading conditions for deformation or seepage failure; Hydraulic barriers and subsoil domain size affect simulation results; and Proposed mitigation strategies' relative effectiveness. The study focuses on a levee cross-section in Ásványráró with one CPT sounding. It models seepage and deformation under expected climate conditions using PLAXIS 2D. The research addresses two-dimensional plane strain, flood and rainfall scenarios, boundary conditions, and mitigation methods.

2. Literature Review

2.1 Overview of levee systems and their functions

Flood-prone areas are protected by levees, which are built of soil, clay, and sand (Tonni et al., 2024). Foundation conditions, material compaction, maintenance, and structural specifications including crest width, side slopes, core composition, and permeability control layers affect hydraulic loading stability. Levees must control water levels and seepage pressures to prevent flooding. Core materials like clay or sand combinations resist seepage, while impermeable blankets and relief wells prevent under seepage and piping.

Fluvial levees along riverbanks prevent riverine flooding, coastal levees protect against storm surges and sea-level rise, and ring levees around cities or industrial zones manage localized floods. Material composition affects performance, with clay cores increasing seepage resistance, structural aspects including crest height and side slopes ensuring stability, and foundation conditions affecting permeability (Robbins et al., 2019). Levees control floodwaters, protect infrastructure, support roads and utilities, and stabilize riverbanks to decrease erosion. Seepage-related failures, especially backward erosion pipes, can cause internal erosion and structural collapse (Tonni et al., 2024). Levees also help reduce flood risk by diverting floodwaters from occupied areas

2.2 Failure mechanisms of levees

Geotechnical and hydraulic causes cause levee failures, but internal erosion, especially backward erosion pipes, is important. High pore water pressures mobilize soil particles, generating seepage channels and sand boils on the landside that can affect structural integrity (Tonni et al., 2024). Overtopping, slope instability, and heave are also important failure processes. Water levels rise above the levee's crest due to extreme rainfall or storm surges, causing surface erosion and possible collapse. Internal erosion occurs when water moves soil particles through the levee, while external erosion occurs when waves and strong currents destroy its surface. Levee geometry and soil conditions can cause slope instability during floods or earthquakes. Liquefaction, lateral spreading, and seismic activity endanger levee stability. Recurring seepage failures highlight the necessity for integrated numerical modelling, monitoring, and risk assessment in levee management. Overtopping accounts for 70.2 % of levee failures, followed by slope instability at 16.7 % and internal erosion at 3.6 %

2.3 Impact of climate change on hydraulic structures

Climate change increases the frequency and intensity of extreme weather events including floods, droughts, and rising sea levels, threatening levee systems. These changes increase erosion, seepage, and hydrodynamic pressures, threatening levee stability. Elevated precipitation and longer storms increase peak river discharges, overtopping, and slope instability threats, while more frequent flooding shortens levee service life and increases maintenance costs. Sea-level rise and greater rainfall increase groundwater levels, causing sand boils and internal erosion (Robbins et al., 2019). Groundwater variations could increase by 30 %, damaging levee foundations. Long-term droughts shrink and crack soil, further affecting levee stability. Historical European flood data show that fluctuating climates accelerate levee foundation deterioration. As sea levels rise, coastal levees experience increased wave action and erosion, requiring flood defence elevation improvements of 1–2 m by 2100. These indications highlight the need for adaptable design, predictive modelling, and improved monitoring.

2.4 Numerical modeling in geotechnical and hydraulic engineering

Numerical modelling helps evaluate levee performance under seepage, piping, and hydraulic loading. Finite element methods are widely utilized for seepage and stability analysis, whereas coupled 1D-2D hydrodynamic and probabilistic models help map flood hazards and estimate risk (D'Oria et al., 2019). Spatial statistical models can identify sand boil patterns (Robbins et al., 2019), Blanket Theory can estimate seepage forces, and Sellmeijer's Model can forecast critical hydraulic heads leading to pipes (Tonni et al., 2024). GIS-based risk mapping visualizes vulnerable zones using historical data and subsurface tests to prioritize maintenance.

Failure probability analysis uses the Monte Carlo method to account for soil property variability, whereas climate model simulations use updated global climate models and land-use scenarios to predict flood risks (Vahedifard et al., 2020). These strategies promote proactive flood management and infrastructure adaption.

2.5 Progress beyond the state-of-the-art

Recent research has advanced the understanding of levee performance under climate-induced stresses through performance-based design and climate resilient assessment (Mainguenaud et al., 2023), probabilistic and coupled hydro-mechanical models (Vahedifard et al., 2020; D'Oria et al., 2019), GIS-based piping risk mapping (Tonni et al., 2024), induced polarization tomography (Ghorbani et al., 2024), and transient seepage monitoring. More recent works in Central Europe, such as (Sheishah et al., 2023; Koch et al., 2023), demonstrated the value of advanced soil characterization in numerical modelling. Most studies rely on simplified hydraulic assumptions or regional-scale data, with limited site-specific geotechnical validation. This study advances beyond existing work by integrating CPT, derived soil parameters with PLAXIS 2D finite element modelling to simulate levee behaviour under both prolonged flooding and rainfall infiltration scenarios. This approach enables a more realistic evaluation of seepage, displacement, and hydraulic gradients, providing a refined, site-specific framework for assessing levee stability and developing climate-resilient flood protection strategies.

3. Study area and data collection

3.1 Overview of studies on the Szigetköz Region

The Danube River shapes the ecologically and hydrologically important Szigetköz region in northeastern Hungary (Figure 1.a). Human interventions and climate change have caused significant environmental, socio-economic, and biological consequences. Environmental monitoring emphasizes sustainable water management to prevent ecological damage. Between Bratislava and Győr, Szigetköz encompasses about 375 km² (Figure 1.b). It protects nearby communities from flooding as an ecological buffer and flood retention zone. The Ásványráró levee is a crucial flood defence that regulates Danube River floods and groundwater levels.

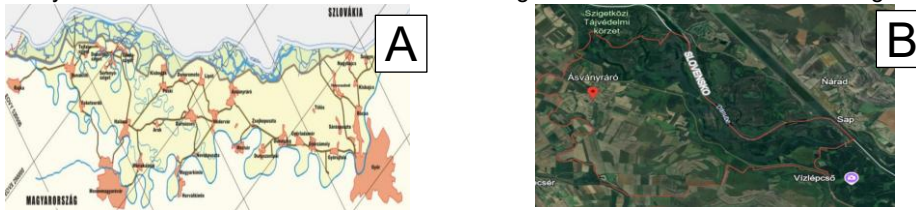


Figure 1: a. Map of Szigetköz region, b. Location of Ásványráró area (source: Szigetkoz.biz and Google Earth)

3.2 Geotechnical and Hydrological Conditions of the Szigetköz Region

The Danube River shapes Szigetköz, one of Central Europe's largest floodplains, with complicated geological, hydrodynamic, and tectonic processes. Groundwater storage and flood control depend on its alluvium, gravel, and sand geology. Long-term fluvial processes have layered Szigetköz's gravel, sand, silt, and clay layers. Due to previous flooding and river meandering, Szigetköz has coarse gravels and fine silts. The base has coarse gravels from high-energy discharge, and alternating sand, silt, and clay layers show flow velocity and depositional conditions. The area has complicated surface-groundwater interactions with fluctuations.

3.3 Climate change scenarios and their expected impact on levees in the Szigetköz region

Northwestern Hungary relies on Szigetköz, between the Danube and its distributary waterways, for flood management. Climate change threatens its flood-control and water-regulation levee system. Climate models predict significant changes in precipitation, river flows, and extreme weather events, which will affect area hydrology and flood control systems. Recent study suggests that increased flood peaks, enhanced erosion, groundwater depletion, and sediment transport alterations could weaken the levee system (Koch et al., 2023). Nearly all levee failures in Hungary between 1954 and 2004 were caused by overtopping, piping, or slope instability. Increasing frequency and severity of heavy rainstorm events may exceed current levee systems' capability. These changes highlight the need for adaptive flood management techniques to address changing hydrological threats and increase resilience to catastrophic storms. In addition to flood threats, climate change is anticipated to lower Szigetköz groundwater levels. Future warming conditions may worsen soil integrity and increase levee subsidence and internal erosion. Variable water levels and material transport patterns promote erosion and jeopardize levee structure. A sediment transport study in Szigetköz found that levee embankments around Ásványráró are highly susceptible to erosion due to irregular water levels. Higher temperatures and dry soils weaken levees, making them more likely to crack and collapse during lengthy floods.

3.4 Existing levee system in Ásványráró

The levee system at Ásványráró is a vital section of the Szigetköz flood protection network (Figure 2.a), protecting adjacent villages and agricultural regions from Danube River floods. Climate change is changing hydrological patterns and increasing flood magnitudes, raising worries about this infrastructure's long-term viability. The Ásványráró levees, initially built to safeguard low-lying communities, have been continually strengthened and lifted to handle larger floodwaters and longer flood events. The levees are 3.5–4 m high and 8 m wide at the top. On the riverbank, their slopes are 1:3 and on the landward side 1:2–1:5 (Figure 2.b & 2.c). Compacted clay, silt, and sand form a semi-permeable barrier to restrict seepage. Although durable, extended immersion during high floods can damage these materials. Previous research found hydraulic and structural issues. Seepage and piping under high flood pressures, slope instability from shifting groundwater levels, and foundation erosion from Danube sediment transport disruptions are examples. To fortify the levee system against climate change stresses, geotechnical monitoring and adaptive reinforcement are needed.

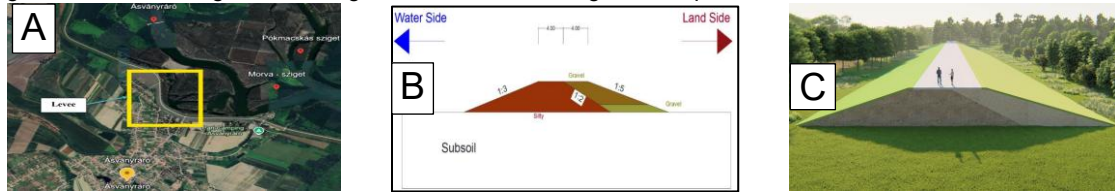


Figure 2: a. Levee study area in yellow box, b. AutoCAD for existing Ásványráró levee, c. 3D model render of existing Ásványráró levee (source: Google Earth and Created by the authors)

4. Methodology

4.1 Numerical modeling approach

Finite Element Method (FEM) is commonly used in soil and rock mechanics to measure deformation, stability, and seepage. PLAXIS 2D is a FEM software for geotechnical structures such as levees, embankments, dams, tunnels, and others. It can analyse stability, deformation, seepage, and stress-strain behaviour in soil and rock under plane strain and axisymmetric conditions, making it appropriate for many geotechnical applications.

4.2 Geotechnical data and parameter determination

To determine levee performance-affecting subsurface conditions, a borehole was bored at Section 24+100. In addition, CPT provided crucial data for PLAXIS 2D numerical modeling. Three soil layers were found in the 10 m borehole: Sandy Silt and Silty Sand from -1.10 m and Sand-Gravel from -6.00 m. The intermediate silty sand has moderate permeability and is prone to internal erosion, while the deeper Sand-Gravel layer has considerable seepage and piping risk during floods. Lack of cohesive clay layers minimizes natural seepage and hydraulic failure resistance. Borehole logs and CPT data revealed four soil strata with varied geotechnical qualities. CPT data were adjusted and processed to obtain soil properties for PLAXIS 2D model inputs. Subsoil depth and grain size affected seepage, stability, and levee reliability at Section 24+100. A surface Sand Silt to Clayey Silt layer protects against cracking in dry conditions, a Coarse to Medium Sand layer supports while allowing water infiltration, and a highly permeable Sand layer at -6.50 m poses a serious seepage and piping hazard during prolonged floods. The levee embankment is made of silt on the water-facing side and a gravel-sand mixture on the landward side. Silt controls seepage but erodes under high water currents. The gravel-sand layer increases stability but introduces seepage due to a highly porous layer one meter below the surface. A 3 m deep low-permeability gravel-sand layer restricts infiltration, preserving levee integrity during floods.

4.3 Climate change scenarios and simulation cases

Historical information, regional climate models, and IPCC recommendations were used to build flood and rainfall scenarios for existing and future hydrological patterns. Four simulation phases represented growing hydraulic loads from river floods and rainfall infiltration. A baseline 3-day flood with a 4 m water height at the crest was simulated in Phase 1. Phase 2 extended the flood to 4 days to reflect climate-changing circumstances. Phase 3 examined sustained saturation and seepage in a climate-driven catastrophic scenario with a 7-day flood. Phase 4 examined infiltration, slope stability, and combined loading scenarios during a 24-h, 5 mm/h rainfall event. The levee model was used in all simulations, with a 100 m subsoil extension on both water and land sides, Open-Closed boundary conditions, and fine mesh discretization. PLAXIS 2D's completely coupled flow-deformation analysis assessed groundwater seepage, pore pressure changes, and soil deformation during dynamic flood and rainfall conditions. An open riverfront boundary allowed water intake while a closed landside boundary prevented lateral seepage. A thin triangular mesh of 15-node elements provided high resolution in

seepage and stress concentration locations. Each simulation began with in-situ stress and steady-state groundwater conditions, then time-dependent hydraulic loading phases imitating floods or rainfall infiltration, and finally transient flow phases capturing seepage and deformation progression. Flood scenarios used hydraulic heads of 4.0 m for 3, 4, and 7 days, while rainfall scenarios used 5 mm/h vertical infiltration for 24 h, examined by fully coupled flow-deformation models.

5. Results and Discussion

5.1 Numerical analysis results

Simulations showed that hydraulic loading duration and type substantially affect levee displacement. Maximum displacement (Figure 3.a) at the landside toe was 0.77 m during a 3-day baseline flood (Phase 1), keeping within acceptable limits. A 4-day flood (Phase 2) caused displacement to grow to 0.88 m, with a quick surge after Day 3 due to rising pore pressures. The 7-day flood (Phase 3) caused the most displacement (1.14 m), suggesting instability with prolonged saturation. The crest and upper slopes were most affected by the 0.86 m displacement from 24 h rainfall infiltration (Phase 4), as rapid infiltration weakened unsaturated soils. These findings demonstrate the cumulative strain of prolonged flooding and the destabilizing effect of severe rainfall.

Different scenarios have different hydraulic gradients (Figure 3.b), which are important for analysing seepage-induced dangers. Rainfall infiltration had the greatest value of 0.1582, indicating substantial upward seepage near the crest. The 7-day flood (Phase 3) had the lowest gradient at 0.0344 due to saturation-induced differential reduction. Short-duration floods had intermediate values due to transient pore pressure effects. This suggests heavy rainfall is more dangerous than continuous flooding for immediate seepage.

Hydraulic loading altered groundwater flow and saturation (Figure 3.c). The 3-day flood (Phase 1) caused 8.45 m³/day groundwater flow, with crest saturation at Embankment 1 at 80-95 %. Though saturation remained high, a longer 4-day flood (Phase 2) decreased flow to 6.45 m³/day due to decreasing gradients. The 7-day flood (Phase 3) had the lowest flow rate (4.35 m³/day) and significant saturation levels, indicating continuous vulnerability. After 24 h of intense rainfall (Phase 4), groundwater flow reached 18.7 m³/day, peaking at 100 % in Embankment 2, indicating significant infiltration and uplift hazards. Long-term floods progressively saturate levees with reducing hydraulic activity, whereas short, intense rainfalls can cause acute infiltration surges and critical saturation, requiring targeted drainage and warning under changing climate circumstances.

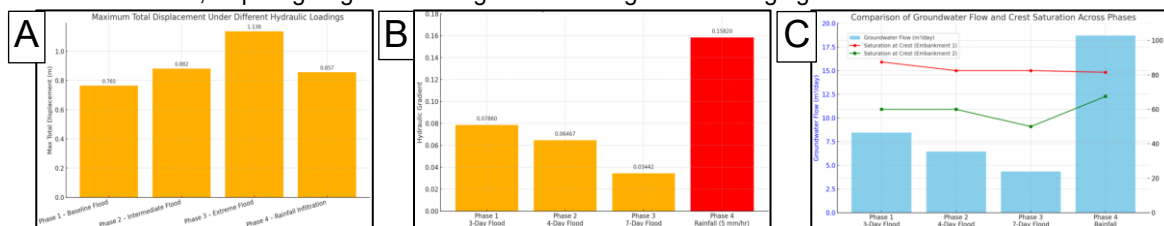


Figure 3: a. Maximum total displacement in each simulation phase, b. Maximum hydraulic gradient in each simulation phase at levee toe, c. Comparison of groundwater flow and crest saturation level for both embankments (source: Created by the authors)

5.2 Flood scenario & Rainfall infiltration comparison

Displacement increased with flood duration, from 0.77 m in Phase 1 to 1.14 m in Phase 3, as prolonged saturation reduced soil strength and raised cumulative stress. Hydraulic gradients, highest in Phase 1 at 0.0786, gradually decreased as seepage stabilized, though extended saturation maintained internal erosion risks. Groundwater flow declined with flood duration, reflecting pore pressure equalization but allowing deeper water infiltration. Rainfall infiltration produced a 0.857 m displacement, with deformation concentrated in upper soil layers due to reduced surface shear strength. It generated the highest groundwater flow at 18.7 m³/day and a peak hydraulic gradient of 0.1582 at the embankment-foundation interface, indicating severe seepage instability. Crest saturation reached critical levels, particularly in Embankment 2, exceeding flood-induced saturation. Despite moderate displacement, the combination of elevated groundwater flow and gradients signals a significant seepage threat. These results underscore the need for levee safety evaluations to incorporate rainfall infiltration scenarios, as conventional designs may underestimate climate-driven rainfall hazards.

5.3 Evaluation of mitigation measures for levee stability

Subsurface cutoff walls (Figure 4a) effectively control levee seepage, with the 14 m sheet pile wall performing best by reducing the hydraulic gradient to 0.00288, groundwater flow to 0.2099 m³/day, and displacement to 0.02565 m. Saturation remained concentrated upstream, confirming effective seepage management. Gravel drainage trenches (Figure 4b) placed at the levee toe proved most effective in lowering displacement to

0.01198 m and reducing the hydraulic gradient to 0.3757, though groundwater flow remained high due to redirected pathways. An extended gravel embankment (Figure 4c) at the landside toe reduced displacement to 0.01614 m and altered flow patterns but offered limited seepage control, with gradients at 0.6683 and moderate groundwater flow. Among the three strategies, the 14 m cutoff wall provided the most comprehensive seepage and erosion control, while toe drainage effectively reduced pore pressure and displacement. The extended embankment improved slope stability but had minimal impact on seepage risks.

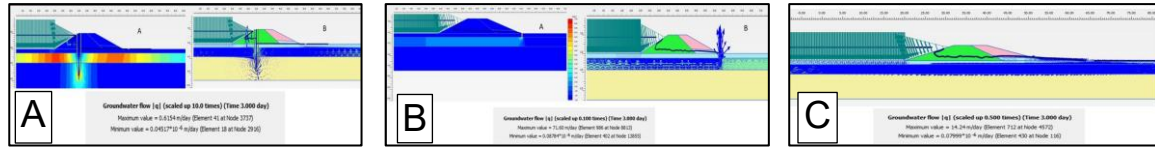


Figure 4: a. Groundwater flow response with sheet pile cutoff wall under flooding, b. Groundwater flow distribution under drainage mitigation near levee toe, c. Groundwater flow plot for extended embankment mitigation (source: Created by author)

Besides the three mitigation measures analysed in this study, other approaches such as seepage berms, relief wells, vegetation reinforcement, impermeable liners, and real-time monitoring systems could further enhance levee stability under changing climatic conditions. These options were beyond the present study's scope but are recommended for future research to provide a more comprehensive assessment of levee resilience.

6. Conclusions

This research examined the Ásványráró levee in Hungary's Szigetköz region, assessing how climate change-driven flood duration and rainfall intensity affect levee stability using CPT data and PLAXIS 2D modelling. Four loading phases simulated real conditions, revealing that longer floods and heavy rainfall increase displacement, saturation, and hydraulic gradients, particularly at the levee toe. Notably, a short, intense 5 mm/h rainfall over 24 h triggered the highest groundwater flow (18.7 m³/day) and hydraulic gradient (0.1582), posing a greater threat than prolonged floods. A 100 m subsoil domain with Open-Closed boundary conditions provided optimal simulation accuracy and efficiency. Critical conditions emerged under rainfall, with gradients nearing failure thresholds and rapid saturation, confirming high piping and slope instability risks. Among three mitigation measures, a 14 m cutoff wall proved most effective, reducing gradients to 0.0029 and seepage risks, while toe drainage cut displacement to 0.01198 m. An extended embankment improved surface stability but offered limited seepage control. The study recommends integrating rainfall infiltration into levee designs, prioritizing deep cutoff walls and toe drainage, enhancing monitoring of high-risk zones, and adopting climate-resilient, simulation-based flood management practices to safeguard the vulnerable Szigetköz levee system.

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