ANALYSIS OF SLOPE STABILITY UNDER VARIABLE WATER TABLE CONDITIONS FOR PRE-MODERNIZED AND MODERNIZED LEVEES

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Abstract

The catastrophic floods in Poland in previous years and the current one in 2024 have highlighted the importance of slope stability in the design, maintenance, and operation of levees, which are crucial for flood protection. While the causes of this year's flood have not been determined yet, as experts are still working on assessing the reasons for the failure of various structures, it is evident that many have failed due to multiple factors, such as overtopping, internal erosion, and slope instability. The article highlights the importance of the observational method, which, during the operation of hydraulic structures often in use for decades, enables data collection on potential seepage through the levee and on adverse filtration phenomena. Such information allows revising previous safety calculations for the structure, adjustments of geotechnical parameters adopted during the design phase, and consideration of factors like the presence of water on the downstream side. Evaluating slope stability under these conditions reflects the actual working environment of the structure and facilitates decision-making regarding potential modernization initiatives.

The article analyses the stability of the levee slope before and after its modernization. A transient seepage analysis through the levee was carried out in the selected cross-section for various water levels, and the stability of the embankment in such conditions was also assessed. Next, the modernization of the embankment was briefly described, with particular emphasis on the sealing system. Stability was evaluated under the new filtration conditions through the levee. Based on this, it was concluded that the sealing system plays a crucial role in improving the safety and stability of the slope. The analysis revealed that remedial actions alone—such as soil compaction and raising the levee crest—without the installation of sealing systems would have virtually no significant impact on the structure safety. After implementing the remedial measures, the levee safety factor can be considered safe, and the numerical analysis of water filtration through the levee indicates that future water seepage on the downstream side during river flooding should not occur.

Keywords: slope stability, transient analysis, levee, sealing systems

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1. Introduction

Throughout history, numerous floods have been recorded along the Odra, Vistula, and other rivers in Poland, both summer floods caused by heavy rainfall and winter floods. This has led to the need for an adequate flood protection system. The system consists of flood embankments, dams, reservoirs (including dry flood protection reservoirs, such as the Racibórz Reservoir, which protected the cities of Wrocław and Opole from flooding), relief channels for the Vistula and Odra and their tributaries, and a system of polders (e.g., the Buków Polder, activated after the 1997 flood). The summer flood in 1997 affected the Odra basin and Poland's largest Vistula River. However, losses recorded in the Vistula basin were significantly lower than those in the Odra basin (Kundzewicz et al., 1999). In 1997, the "Millennium Flood" revealed numerous weaknesses in Poland's levee systems, many of which had not been adequately modernized. The floodwaters exceeded design levels, overtopping levees that had steep slopes and inadequate reinforcement. When the water pressure increased, slope instability resulted in breaches, with rapid erosion occurring on the water-facing side of embankments. The lack of proper slope design, poor maintenance, and the absence of modern stabilization techniques, such as the use of geotextiles and riprap, were identified as fundamental causes of failure (Włodarczyk, 2021; Kundzewicz et al., 1999). The 2010 flood, while slightly less destructive, highlighted persistent issues with slope stability. Prolonged high water levels and continuous rainfall saturated the soil in the levees, increasing pore water pressure and weakening the internal structure of the embankments. Levees in areas such as Kraków and Sandomierz failed again due to slope instability, highlighting that the need for slope stabilization remained substantially unaddressed despite improvements made after 1997 (Kundzewicz et al., 1999).

Several technical factors, including the steepness of the slope, soil composition and compaction, water infiltration, and drainage capabilities influence slope stability in levees. In numerous instances across Europe, the USA and Poland, many levees and dams had been constructed with steep, unstable slopes that lacked proper reinforcement, making them vulnerable to rapid erosion during flood events (Van et al., 2019, Rossi et al., 2021). Modernizing Poland's flood security infrastructure requires focus on improving slope stability through various means: (1) flattening slopes, (2) incorporating geotextiles, (3) installing vertical sealing systems, and (4) improving drainage systems. The effectiveness of securing damaged flood levees with GCLs on the Odra River was demonstrated, for instance, by Stępniak (2008), while the impact of such sealing systems on levee slope stability was presented in Kołodziejczak's (2007) study. In this work, the results of levee stability calculations for four different types of sealing systems showed that the obtained factor of safety exceeded the required value in each case – the best results were achieved for levees sealed with a bentonite mat within the body and a clay cut-off wall.

This article aims to present the role of geosynthetics in modern hydro-technical construction and their potential applications in upgrading structures in poor technical condition. Temporary repairs and soil compaction alone are insufficient – sealing materials can significantly improve the safety and stability of structures during floods. The article comprises calculations in conditions of variable water flow through levees, compares the stability of a levee under different modernization scenarios, and relates the stability assessment results using the classical approach to the methods proposed by Eurocode 7.

2. Material and Methods

2.1. Site Characterization of Pre-modernized and Modernized Levee

The section of the levee analysed in this article is the right flood levee of the Vistula River in the Maciejowice Valley area. The levee was modernized in recent years due to the threat to the levee posed by local stability loss consisting of filtration deformations, which, in extreme cases, could lead to a general stability failure. The study examined a selected levee cross-section characterized by the most challenging geotechnical conditions – in almost the entire embankment cross-section, loose soils dominated. From the ground surface to about 1 metre deep, measured from the crest of the embankment, it was composed of fine sands (FSa). The sands were in a loose state with a relative density of about D_r=0.25. The subsurface consists of silty sands (siSa) with a thickness of 2–2.5 metres, underlain by medium sands (MSa) with interlayers of clayey sand (clSa), with the base of the layer not determined. Calculation parameters were based on archival data, dynamic probing, and tested soil samples, as summarized in Table 1.

The observational method was used to evaluate poor technical conditions of the levee before modernization. According to Eurocode 7 (EN, 1997) is a geotechnical design approach that allows monitoring the behaviour of a structure during its construction or operation and adjusting the design, if necessary, based on observed performance. It is particularly useful in situations with uncertainty as to the geotechnical conditions or where the consequences of failure are estimated. Such observations and data from previous years revealed that the levee experienced significant seepage during previous flood events through its body and piping, with water emerging at the downstream toe (Figure 1). This allowed incorporating these observations into the analysis of water flow through the levee and the stability assessment, considering water flow through the levee and its accumulation on the downstream side.

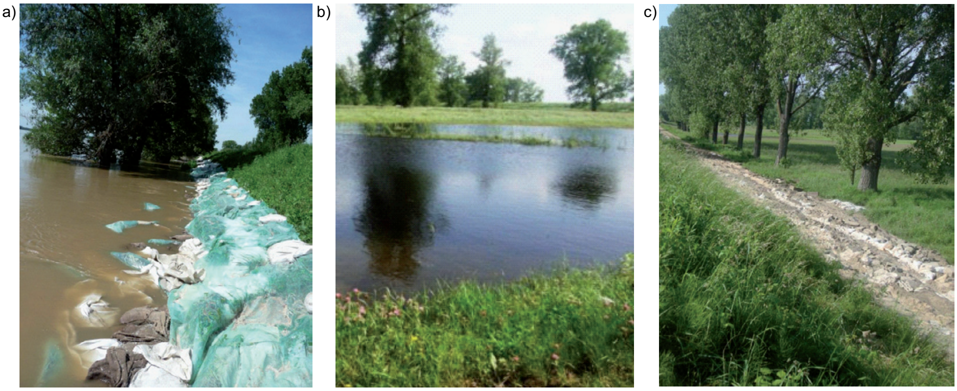

Figure 1. View for the investigated levee during the flood in 2010 (a), the upstream side covered by water seeping through the levee (b), and damages after the water has fallen (c) (Kronik, 2012)

Table 1. Geotechnical parameters of soils

Type of soil	Relative density Dr [-]	Effective internal friction angle φ [°]	Compressibility mv [1/kPa]	Saturated volumetric water content n [-]	Hydraulic conductivity k [m/s]
FSa	0.25	29	0.00035	0.37	$5.0\text{x}10^{-4}$
siSa	0.45	31	0.00025	0.38	$8.1\text{x}10^{-6}$
MSa_clSa	0.5	33	0.001	0.34	$1.7\text{x}10^{-3}$
FSa/MSa (after modernization)	0.55	33	0.0007	0.34	$5.0\text{x}10^{-4}$

Modernization work primarily involved compacting the body of the existing levee and raising it – the crest was lifted by one metre. Medium sand, well-graded, was used for construction work, resulting in a relative density value of D_r=0.55. Figure 2 shows the view during compaction of the levee slope, hydraulic barrier construction work at the base of the embankment, and the view after completion of the modernization. The downstream, upstream, and levee crest were also reinforced with a humus layer and seeded with a grass mixture. On a particular section of the levee, the toe of the downstream slope was reinforced with concrete slabs.

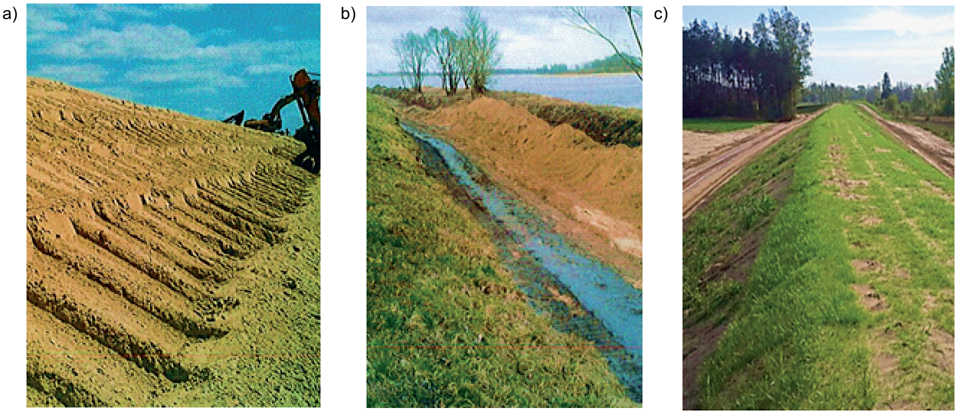

Figure 2. Compaction of the slope (a), construction of a cut-off wall (b), and the final result of the modernization work (c) (Szurowski, 2017)

Non-cohesive soils (mostly medium, fine, and silty sands) enhance water filtration under the levee base during water accumulation, creating a significant risk of adverse effects caused by water filtration, such as suffusion and hydraulic piping. The body of the analysed levee section was constructed from local soils sourced from floodplain areas, primarily fine sands. Additionally, the loose condition of the soils in the levee body and its foundation caused frequent problems with seepage through the levee and its foundation on the downstream side in the years before modernization. Therefore, installing a sealing system was a key treatment during the levee modernization. The levee body was sealed, and the filtration path from the river was extended by installing a vertical bentonite-cement cut-off wall. Such impermeable barriers made of cement-soil suspension are commonly used in hydraulic engineering, drainage systems, and even around waste disposal sites. The available literature has extensively described these methods (e.g., Stępniak, 2008; Skutnik et al., 2019; Polańska & Rybak, 2020).

The mixing of suspension with the soil is performed using various cutting-mixing equipment, including specially adapted drilling rigs (*Deep Soil Mixing* – DSM), trenchers (*Continuous Deep Mixing Method* – CDMM), or cutting-mixing drums (*Cutter Soil Mixing* – CSM) (Polańska & Rybak, 2020). The vertical sealing system on the downstream side was implemented using the CDMM method (Figure 2b) with a specialized cutting trencher for the analysed project. This method involves continuous deep soil mixing with bentonite-cement slurry fed in real time. The designed depth of the cut-off wall is achieved by adjusting the depth of the movable cutting element, the length and blade angle of which are tailored to the required elevation of the cut-off base (Rychlewski, 2018). The levee body was further sealed with a bentonite mat (GCL). Geosynthetic clay liners consist of dry bentonite (typically 5 kg/m^2 of dry sodium bentonite is used to produce GCLs (Holtz et al., 1998)) supported between two geotextiles or a geomembrane carrier, as illustrated in Figure 3a–d (Koerner, 1994). Bentonite has a moisture content ranging from 6 to 20% in its dry state, swells, and forms a very low permeability barrier when wetted – fully hydrated bentonite typically has a permeability range of 1 to 5 × 10^{-11} m/s. The geotextiles above and below the dry clay may or may not be bonded with threads or fibres to enhance the in-plane shear strength of hydrated GCLs. These liners are supplied in roll form. Figure 3e (Szurowski, 2017) shows the installation of a barrier on the downstream slope of the analysed levee section. The GCL was laid on the newly built layer, anchored at the crest to prevent the sealing from rolling up, and covered with a layer of soil. The slope on the downstream side was additionally protected with a mesh to shield it from mechanical damage and the impact of animals.

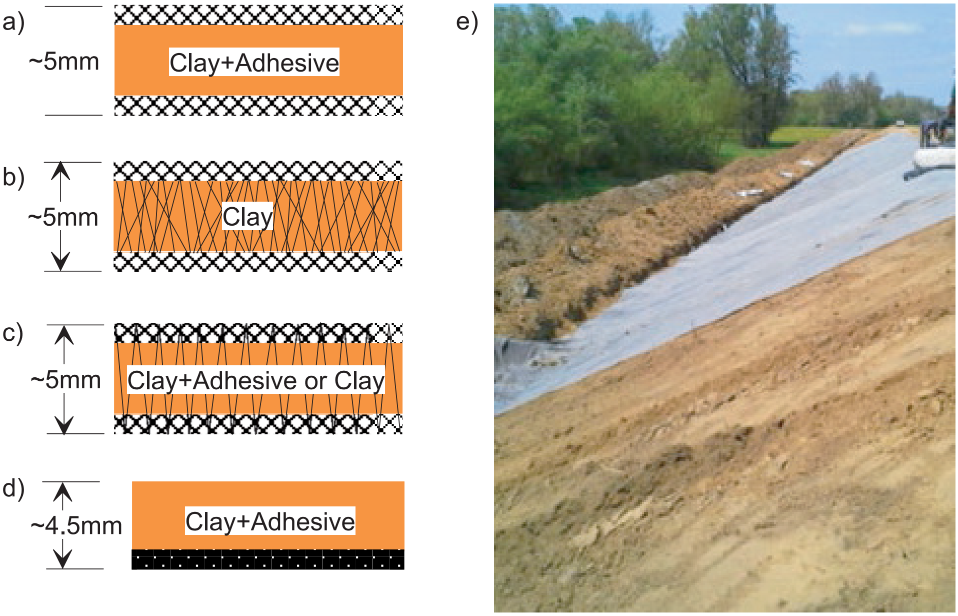

Figure 3. Geosynthetic Clay Liners: a) geotextile/clay/geotextile, b) stitched, bonded geotextile, c) needle woven geotextile, d) clay liner on PE geomembrane, e) laying the GCL mat on the analysed section of the levee

Below is a diagram (Figure 4) showing the structure of the levee, the foundation, and the materials from which they are made. The diagram also presents the scope of modernization work and the location where the sealing system is installed on the structure – the GCL mat and the vertical barrier. The diagram indicates the water levels impounded by the levee, which were assumed for the calculations and are referenced in the following text.

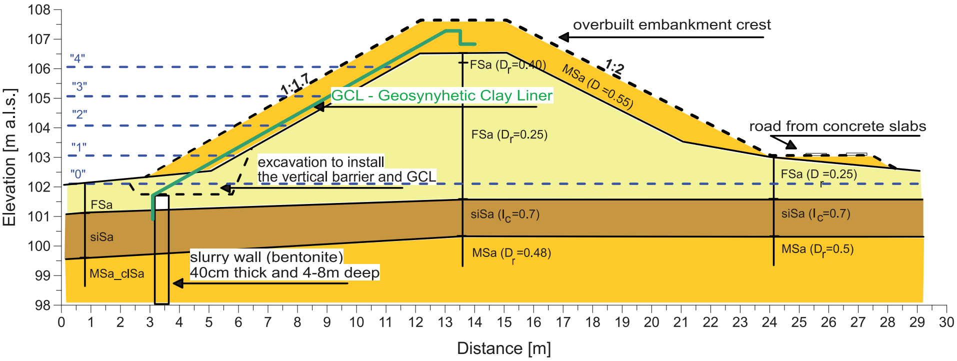

Figure 4. Cross-section of embankment under consideration – diagram before and after modernization works (marked in red); location of the sealing system and water levels impounded by the structure

2.2. Slope Stability – Limit Equilibrium Method

Studying the stability of natural and man-made slopes is a significant issue in geotechnical engineering. It is crucial because even the slightest slope failure can lead to severe financial losses and may even endanger human lives. The issue of slope stability should be carefully considered before, during, and after the completion of building of any structure. Roads, railway embankments, earth dams, flood protection levees, etc., are subject to such assessments (e.g. Kłosiński and Leśniewski, 2009; Wysokiński et al., 2011; Zydroń and Gruchot, 2014).

There are various methods for calculating the factor of safety for both natural and man-made slopes, including the limit equilibrium method, finite element method, finite difference method, discrete element method, as well as backward analysis and probabilistic methods (e.g., Monte Carlo). Among these methods, the *Limit Equilibrium Method* is the traditional approach used to analyse slope stability, in which the factor of safety (FoS) is calculated to predict the stability of the slope.

The *Limit Equilibrium Method* requires the balance of forces or moments resulting from the stresses acting on the slope and the mobilized shear strength along the slip surface. Comparing these resisting and driving forces allows the determination of the minimum and most critical slip surface. The method calculates the safety factor by comparing the shear strength along the slip surface with the required force to keep the slope in equilibrium. In the case of shear-type failures, the material is considered a Mohr-Coulomb material (Wyllie and Mah, 2004). As suggested, static equilibrium can be achieved in two ways: the first method involves considering the equilibrium of the entire soil mass and then solving for the free body; the second one divides soil into multiple slices, with each slice having to satisfy the equilibrium condition of all forces – Figure 5 (Wright, 2005).

The limit equilibrium method with slicing is widely used among engineers and researchers owing to its well-established and traditional approach. This "slicing approach" became widely adopted in the 1950s and 1960s. Since then, various slicing methods within the limit equilibrium framework have been thoroughly examined and compiled (Fellenius, 1936; Bishop, 1955; Janbu, 1954; Price and Morgenstern, 1965; Spencer, 1967; Fredlund et al., 1981; Duncan, 1996).

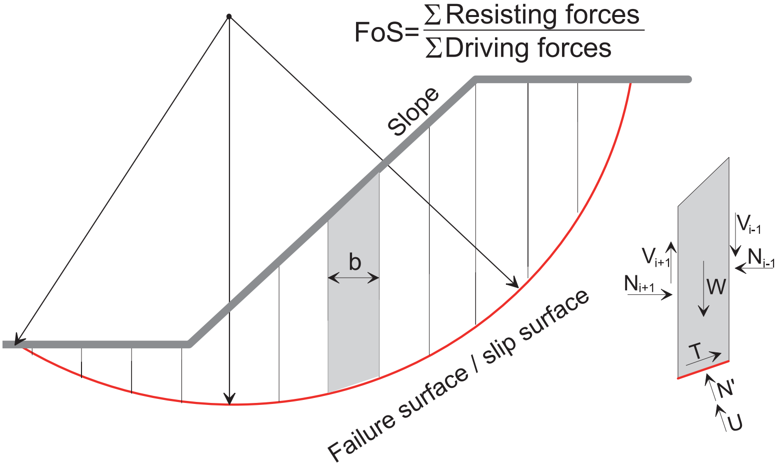

Figure 5. Illustration of the Method of Slices; forces acting on a typical slice: the weight of soil above the failure surface – W, the interslice reactions from the adjacent slices – N_{i-1}, N_{i+1}, V_{i-1}, V_{i+1}, the reaction of the stable ground which consists of a normal effective force – N', shear component T, and the boundary water force – U

The calculations were performed using the GeoStudio2024 Slope/W software, applying the classical approach, i.e., without considering the partial factors recommended for stability calculations by Eurocode 7. It should be noted that applying partial factors by Eurocode 7 would reduce the final calculation result (or, more precisely, the term *Overdesign Factor* – ODR should be used in this context). However, for an actual structure after completed embankment modernization, the authors compared the calculation results based on the adopted computational approach, including the partial factors recommended by Eurocode 7.

3. Results

3.1. Filtration Analysis

The water flow calculations through the levee were performed using the GeoStudio2024 Seep/W software. Partial soil saturation was assumed within the levee and directly beneath it, particularly in the fine sand layer. In contrast, the silty and medium sand layer of the foundation was considered fully saturated. Figure 6 presents example graphs illustrating the relationships between volumetric moisture content and hydraulic conductivity as a function of matric suction for fine sand, which was used in the calculations. However, estimating changes in the hydraulic conductivity coefficient posed challenges. While increased compaction most likely reduced the water flow through the levee body, the embankment was raised using medium sand, which has a higher hydraulic conductivity than fine sand. Consequently, the filtration coefficient was assumed unchanged for post-modernization calculations.

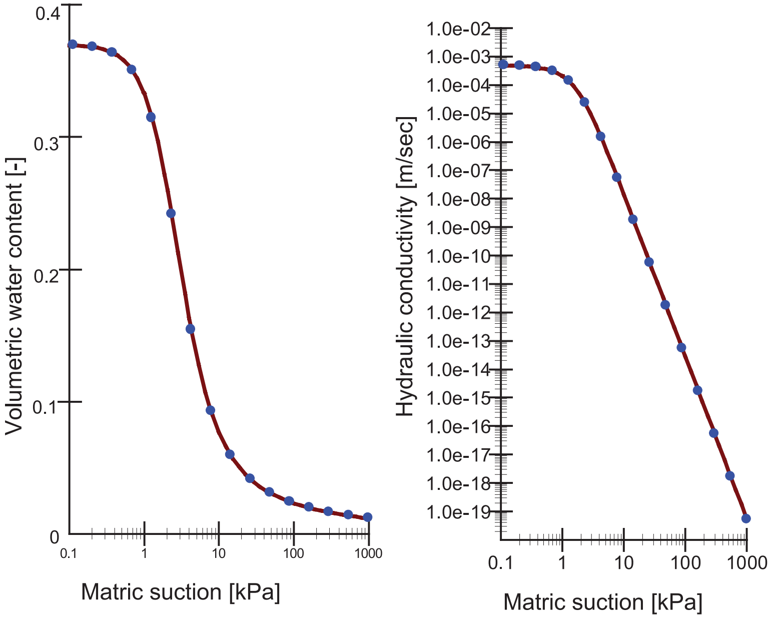

Figure 6. Volumetric water content and hydraulic conductivity functions of fine sand for pre-modernized conditions

A water flow analysis was carried out considering 5 water levels, including a baseline representing the groundwater table (Figure 4 in Chapter 2.1). The water level labelled "5" corresponded to the design flow, while level "1" represented the groundwater level. The stability calculations for the downstream slope included three scenarios: before the modernization of the structure, after modernization without the installed sealing system, and the final scenario incorporating sealing with a GCL mat and a 4-meter-long vertical barrier.

The authors used transient analysis in calculations because it allowed them to take into account time-dependent changes in water flow through the levee, providing a more accurate representation of how the system responds to varying hydraulic conditions, such as rising and falling water levels during flood events. According to the assumptions, it was accepted that the water level would rise by 4 metres over 2 days, with an increase of 10 cm every 72 minutes. Calculations were also performed for the upstream slope in the case of a lowering of the water table, on the assumption that the recession time of the flood wave would be 4 days.

3.2. Slope Stability Evaluation

The landside slope stability calculations considered pre-modernization and post-modernization scenarios. Pre-modernization analyses revealed a safety factor 1.631 for dry slope conditions with groundwater 0.5 metres below the surface (Figure 7). However, when water was impounded at the design flow level, the minimum value in the flood episode FoS dropped to 1.199 (in the 43rd hour). After further 6 hours, the FoS increased to 1.222 due to a decrease in the hydraulic gradient. This lowest FoS value occurred 39 hours and 48 minutes after the onset of the water wave. This shows that this minimum value would not have been detected if the calculations were conducted under the assumption of a steady state. The transient analysis allows for a more reliable slope stability assessment during such dynamic changes during a flood. The below table presents calculation results for the flood event at selected times and water levels impounded by the levee. These results highlight the critical impact of water filtration on levee stability – while a dry slope provides high stability, prolonged water impoundment and saturation significantly reduce stability, potentially leading to failure.

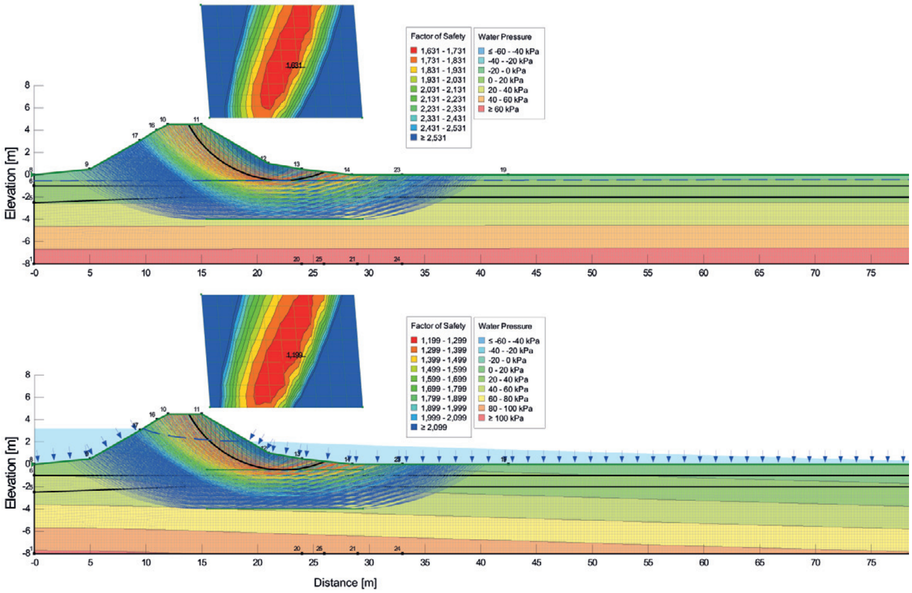

Figure 7. Diagram of the critical slip surface and calculation results for the embankment before modernization, considering the groundwater level (a) and water level corresponding to the design flow (b)

Modernization efforts, particularly soil compaction and the installation of sealing systems, played a crucial role in improving both filtration characteristics and stability, demonstrating the importance of such measures in levee safety. The diagram of the critical slip surfaces and the calculation results for the modernized embankment without sealing and with sealing systems in two variants are presented in Figure 8. Without implementing sealing on the slope and in the embankment foundation, the obtained factor of safety value is 1.324, which differs only slightly from the pre-modernization condition – a difference of 0.125. It is difficult to determine whether this represents a sufficient improvement in the condition of the structure as compared to the effort and costs incurred. However, this is a hypothetical situation, as such a variant was not considered in the modernization project (it may have been considered but was not implemented).

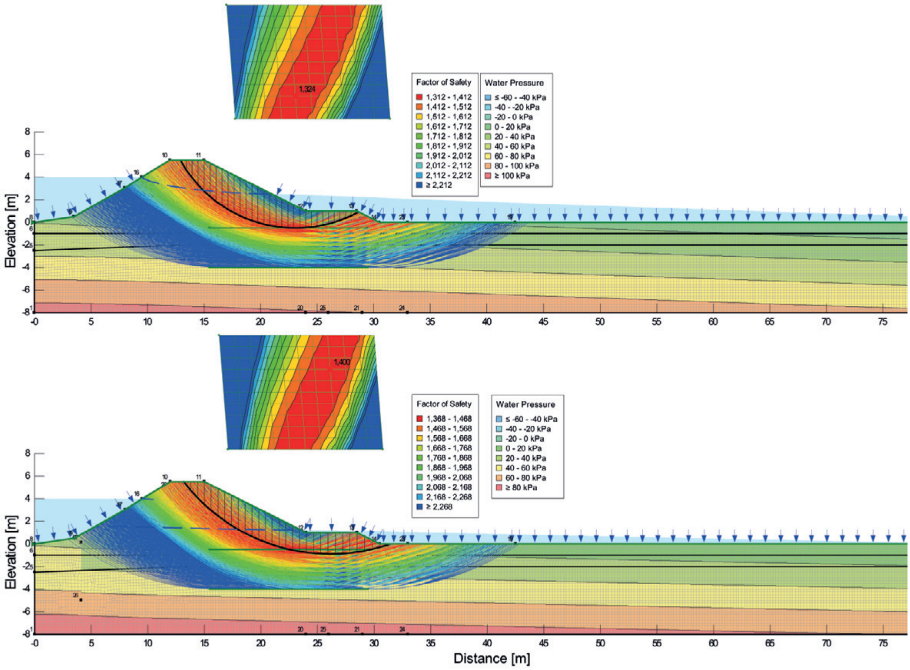

Figure 8. Results of stability analysis for the modernized levee at a water level corresponding to the design flow: no sealing (a) and sealing system installed (b)

The calculation results for all variants of water impoundment and levee constructions are summarized in Table 2. The stability analysis revealed a critical Factor of Safety (FoS) of 1.209 in design flood conditions, marginally above the failure threshold (FoS = 1.0). After modernization, calculations confirmed significantly improved FoS values for various water levels. Without a sealing system, the improvement was minimal, with the FoS increasing from 1.199 (pre-modernization) to 1.324. With a GCL mat and a 4-metre vertical barrier, the FoS increased to 1.400. Although this is not a significant increase in the safety factor, it already provides a 40% margin when considering the advantage of stabilizing moments over sliding forces. On the other hand, the water level on the downstream side is noticeably lower than if there were no slope sealing.

Table 2. Calculation results for various water impoundment scenarios and levee constructions

Time [h]	The factor of safety FoS [-]		
	Before modernization	Modernized (no sealing system)	Modernized (GCL+4m vertical barrier)
0	1.631	1.814	1.814
2	1.631	1.814	1.814
4	1.630	1.814	1.814
6	1.625	1.811	1.811
8	1.607	1.804	1.804
10	1.583	1.793	1.796
12	1.545	1.762	1.782
16	1.432	1.682	1.744
20	1.320	1.611	1.697
24	1.238	1.530	1.634
30	1.215	1.430	1.584
36	1203	1.352	1.510
39 48’	1.199	-	-
42	1.206	1.336	1.430
48	1.222	1.324	1.400

They should be plotted on a graph to enable a proper analysis of the obtained results (Figure 9). An analysis of the water table and the Factor of Safety reveals a strong nonlinear relationship between the time (water level) and levee stability. This is particularly noticeable between the 12th and 24th hour of the river water rise. As regards the embankment before modernization, the decrease in slope stability is more pronounced than after its modernization. Comparing the post-modernization state with and without sealing, we can observe that sealing slows the FoS response over time.

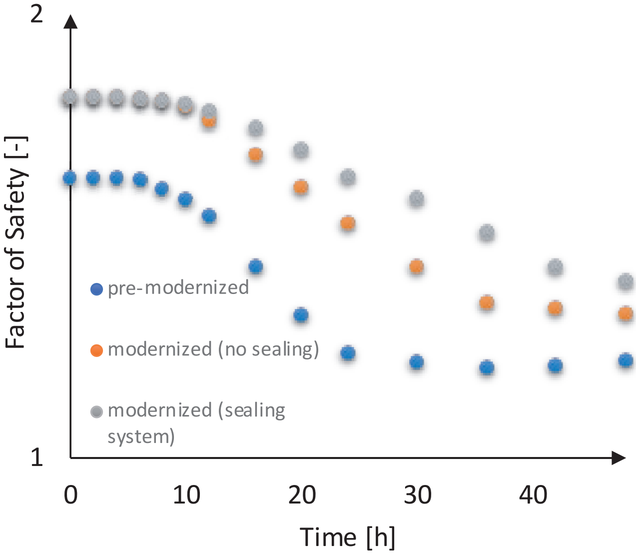

Figure 9. FoS variation over time for different scenarios

The calculations also considered the stability of the downstream slope during the lowering of the water table. Assuming that after the embankment modernization, the initial FoS was 1.537, the water level rise caused an increase in the stability coefficient due to water pressure on the slope. As the water table gradually returned to its initial level over four days, the FoS continued decreasing steadily to its original value. However, when assuming that the water receded within just four hours (e.g., due to an embankment breach upstream of the analysed section), the FoS for this scenario dropped to only 0.944.

If an analysis of the selected case were based on the calculation results using various approaches proposed by Eurocode 7, it could be concluded that the highest stability values are obtained with the DA1-1 method. In contrast, the lowest values are found using the partial factors from the DA-3 approach, which is recommended for use in our country. The calculations for the embankment after modernization with sealing (i.e., the existing variant) are shown in Figure 10. The lowest values of ODF (Overdesign Factor) were obtained for the DA3 approach, with ODF = 1.095, and this value can be considered safe from the perspective of embankment stability.

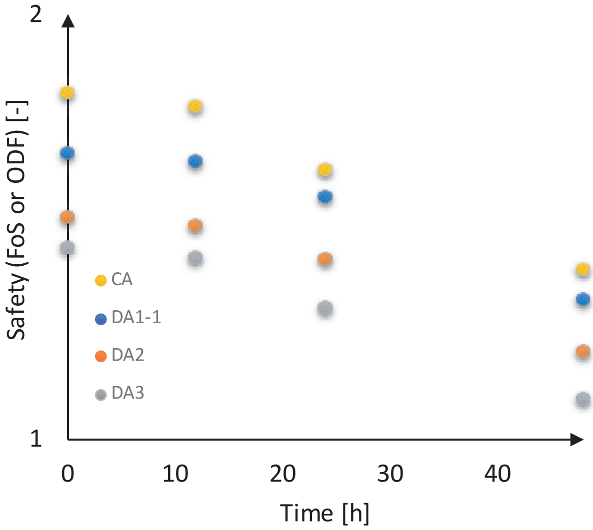

Figure 10. Factor of Safety (for classical approach) and Overdesign Factor (Eurocode 7) variation over time for modernized levee

In the case of the classical approach (CA), the obtained values of the stability coefficient are numerically higher than the calculation approaches proposed by Eurocode 7. However, this raises the question of what value of the Factor of Safety should be considered as the minimum required. Should it be a value of 1.2, in which case the embankment can be considered safe, or should a higher value, such as 1.5, be assumed? If the latter one, it would be necessary to reconsider whether the geometry of the embankment should be improved or additional earth (filtration) supports should be applied on the downstream side.

4. Conclusions

The ongoing modernization of numerous flood protection structures, particularly the installation of sealing systems and soil compaction, has effectively improved the stability of levees and reduced the risk of failure during floods. This article emphasizes the critical role of sealing systems in enhancing safety and also highlights the need for continuous modernization and maintenance of flood protection infrastructure. The data comprised in the analysis can be interpreted both in the context of immediate results and from the perspective of future optimizations, technical dependencies, and opportunities to increase the efficiency of modernization.

The article presents an example of a modernization of an existing flood protection levee. The levee slope stability calculations were carried out, considering several water levels and modernization variants. Based on the above analyses, it can be concluded that:

1) the slope stability analysis of the embankment during a rapid water level rise in the river should not be limited to a steady-state condition but should be based on transient analysis, which considers time-dependent changes and the response of a levee to flooding;

2) the decrease in the stability coefficient during water rise is the most rapid for the embankment before its modernization. Meanwhile, it changes the least after modernisation and the application of sealing ;

3) the safest approach was DA3, in which the lowest calculated ODF value for the modernized embankment was 1.095. According to Eurocode 7, this should provide an adequate safety margin.

In summary, it can be concluded that installing GCL mats and a vertical barrier on the structure significantly improved slope stability, confirming their critical role in enhancing the reliability of levees during extreme floods.

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