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Research paper

Assessment of the risk of road embankment instability due to water filtration using fully coupled numerical analysis

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Abstract: The cut-off walls of infrastructural ground structures are a vital aspect of geotechnical engineering, with the array of available technologies in this domain continually expanding. Polyvinyl chloride (PVC) sheet pile walls are gaining popularity and have become a significant choice in design solutions, despite the long-standing recognition of sheet pile walls in their traditional steel form. This paper presents a case study focusing on a road embankment of a Provincial Road number 181 in Poland. It provides a historical perspective of the embankment, details the soil and water conditions of the area, and conducts an extensive analysis of filtration through embankment at various construction stages using the Finite Element Method. The study offers insights into the three-dimensional model, incorporating a fully coupled stress and seepage analysis. The results encompass water flow paths, slope stability, and displacements before and after the construction of the impermeable barrier, providing a comprehensive view of this modern and eco-friendly engineering solution.

Keywords: cut-off wall, FEM, slope stability, road embankment, sheet pile wall

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1. Historical outline and the background of the problem

The analyzed road embankment of Provincial Road No. 181 is located on the left bank of the Noteć river, approximately 1.2 km from the riverbed, in the valley of an unnamed watercourse, commonly referred to as „Struga”. The localization of the embankment is depicted on a fragment of a historical map in Figure 1. In the 16th century, a river dike was built, followed by the damming of water and creation of artificial reservoirs (ponds). This development provided an opportunity to build a mill, which, according to the source [2], marked the beginning of settlement in this area. The ruins of the mill can be observed today on the northwest side of the embankment.

Fig. 1. Fragment of a historic map with marked embankment

In addition to mining, the village was historically famous for its industrial traditions including metallurgy, which utilized local deposits of bog iron. Its proximity to the river Struga allowed for the operation of forges. The embankment continues to serve as the primary transportation route connecting the cities of Drawski Młyn and Wieleń. In 2019, water exudates were observed on the northwest side of the embankment. The suspected migration of the water from the artificial reservoir through the embankment raised concerns about potential damage or even the destruction of the road embankment. These observations prompted the investor to commission comprehensive geotechnical tests and subsequently a project to characterize repair work aimed at safeguarding the embankment against the infiltration of water from the reservoir, which posed a safety threat.

2. Description of the research area and its ground-water conditions

In 2020, field and laboratory tests were conducted to prepare geological documentation [2]. The research results presented in the document served as the basis for designing seepage barrier, whose purpose was to control water filtration through the embankment body. The road's grade line ranges from approximately 41.8 m above sea level (in the eastern part) to around 41.5 m above sea level (in the south-west part). The provincial road transverses a high embankment, reaching a height of about 5 m, extending from the bottom of the valley on the southwest side. During the research, the water was drained from the reservoir, and its original level, which was stabilized at an elevation of approximately 38.5 m above sea level, decreased by about 2.4 m, ultimately stabilizing at an elevation of roughly 36.1 m above sea level.

2.1. Geological structure

Based on the archival documentation [2], the research identified Quaternary Pleistocene deposits resulting from ice sheet accumulation during glacial periods, overlain by Holocene sediments from swamp-river accumulation. The embankment itself consists of anthropogenic man-made ground.

The oldest sediments in the substrate are the moraine sediments of the Central Polish Glaciation (III package), including moraine tills with numerous sand pockets. The top layer of the moraine tills consistently found in every borehole at a depth ranging from approximately 2–10 m below the surface, corresponding to elevations of around 28.5–38.5 m above sea level. In the stream valley, above the moraine tills, there exists a substrata layer of residual Holocene sediments of swamp-river accumulation (II package), consisting of peat, fine mud, gravel, sands, organic sands and tills.

The total thickness of these sediment deposits varied significantly, ranging from 1 to 8 meters below the surface. The present Provincial Road No. 181 (DW 181) embankment was constructed on these residual sediments, which include both mineral and organic components. The embankment is composed of a mixture of non-cohesive soils, encompassing fine sands, gravels and locally, humus admixtures. The compaction levels of the soils forming the embankment vary, ranging from very loose to compacted.

2.2. Geotechnical conditions

The geotechnical cross-section analyzed in the model represents the sediments described in chapter 2.1 Geological structure. Within the cross-section (Fig. 2), following soil layers are identified:

– Loose anthropogenic soils belonging to package I, primarily composed of sands, organic sands, gravels with occasional admixtures of brick rubble and humus. CPTu probe results indicated that these soils exhibit average cone resistance (q_c) values ranging from 2.4 to 3.7 MPa and friction ratio (R_f) ranging from 0.4 to 2.2%.

– Organic and non-cohesive loose soils of package II comprise peats, aggravate muds, gyttjas, organic sands, and gravels. CPTu probe results indicate that these soils exhibit average cone resistance (q_c) values of 1.0 MPa and friction ratio (R_f) ranging from 3.0 to 9.0% for organic soils. Loose, humus sands are characterized by average cone resistance (q_c) values ranging from 2.5 to 3.2 MPa and friction ratio R_f of 0.3 to 1.8%.
– Package III includes hard plastic and semi-stiff cohesive soils. These soils consist of sandy clays and exhibit average cone resistance values q_c ranging from 2.6 to 5.2 MPa and friction ratio R_f falling within the range of 2.2 to 4.5%.

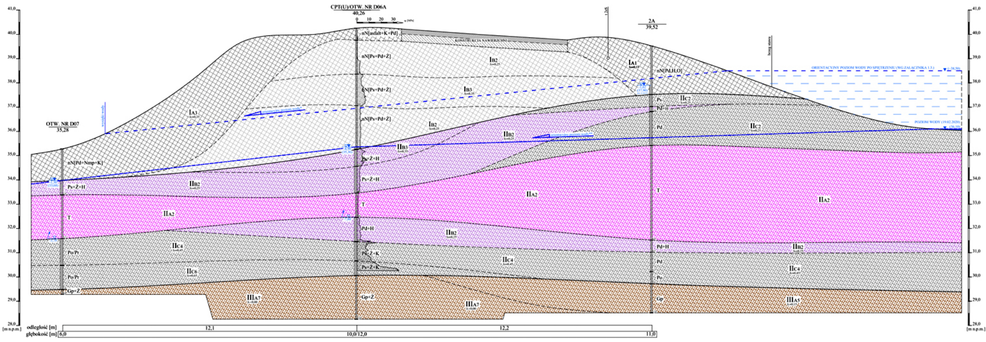

Fig. 2. Characteristic cross section through the embankment, indicating location of the cut-off wall; the blue dashed line symbolizes the approximate water level after damming; the solid blue line represents the water level after dewatering of the pond

2.3. Hydrogeological conditions

In the substrate of the analyzed section of the DW 181 road, the existence of one quaternary water level was found in the form of either free or confined water table in river sands. In case of confined water table, confining layers are organic soils and silts.

The hydrogeological conditions of the analyzed area are closely related to the watercourse – the river Struga, crossed by a dike, damming the water in an artificial reservoir (pond). With the damming of Struga water, the water in the pond stabilizes at 38.5 m above sea level. During research, in February 2020, the water from the pond was drained, at a level of about 2.4 m lower, at 36.1 m above sea level.

The results of the research indicate that the dike, and now the road embankment, was formed directly on swamp-river sediments, largely organic sediments. The embankment is made of multi-grained sands, with the filtration coefficient (determined based on the grading curves) ranging from 7 to 13 m/day [2]. The depths and fluctuations in the groundwater level near the embankment are clearly related to the water level in the pond – fluctuations mainly depend on the degree of filling.

3. Assumptions of the analysis

3.1. Contextual Framework and Assumptions

The concept behind the implementation of an anti-filtration barrier was to mitigate filtration through the road embankment, as prolonged filtration could potentially compromise its stability. Given the substantial volume of organic soils with weak filtration properties and the absence of soil pressure transmission, the idea emerged to employ a lightweight and impermeable structure capable of effectively restricting flow and could be introduced into organic soils without the risk of submersion. Additionally, uncertainty arose regarding the aggressiveness of the organic soil environment towards the barrier material and the potential long-term corrosion, which could result in water leaks. The technical solution addressing all these aspects is an impermeable sheet pile wall made of polyvinyl chloride (PVC). The methodology aimed at confirming the hypothesis involved conducting a coupled analysis of stresses and filtration using the finite element method to examine both the pre- and post-installation states of the barrier, as well as stability calculations of the embankment before and after construction. The numerical calculations were carried out within the Midas GTS NX program, dedicated to solving geotechnical problems [1].

Based on the detailed data from geological documentation, the subsoil, the embankment with the existing road surface, and dammed water in the artificial reservoir were modeled, taking into consideration different levels of filling. In the model, the natural water level in the reservoir was set at 38.5 m above sea level. Subsequently, for construction purposes the water was drained to the level of 36.1 m above sea level and then refilled to its original level. The purpose of the barrier was to alter the filtration path through the road embankment and to prevent water exudates on the western side of embankment's slope. The assumptions were validated through numerical calculations.

Additionally, in the coupled analysis, the stability of the embankment was checked in three construction phases:

– in the existing state, with the water in the pond stabilized at 38.5 m above sea level,
– after the water was drained through the culvert and lowering it to the level of 36.1 m above sea level,
– after the construction of the anti-seepage barrier and refilling the reservoir to the original level of 38.5 m above sea level.

3.2. Modeled substrate

The substrate was designed using data from geological documentation, resulting in the soil substrate and construction model (Fig. 3). For natural soils Hardening Soil constitutive model was used. It is an elasto-plastic model, with an additional cap yield surface that encloses the elastic domain in stress space ($p - q$) on the hydrostatic (p) axis. The cap allows for simulating the densification/compaction of the material. The model represents the behavior of the soil in elastic-plastic zone, with hardening related to the stress path. Based on data from the geological documentation, the following parameter values were derived:

- Secant Stiffness Modulus E_{50},
- Oedometric Primary Modulus of Compression M_0,
- Elastic Modulus at Unloading E_{ur},
- Reference pressure p_{ref},
- Poisson's coefficient ν,
- Volumetric weight of saturated soil + weight of water γ'',
- "At rest" earth pressure coefficient K_0,
- Porosity coefficient e_0,
- Power for stress-level dependency of stiffness m,
- Porosity n,
- Cohesion c,
- Change of cohesion Δc,
- Angle of Internal Friction φ,
- Dilatation angle Ψ,
- Overconsolidation ratio OCR.

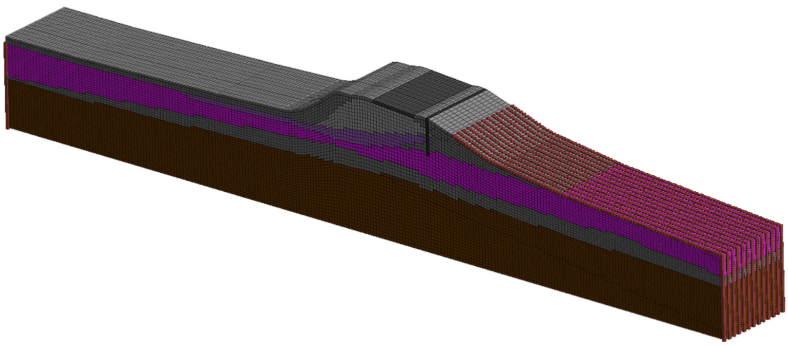

Fig. 3. Model view

3.3. Water flow

In addition to kinematic boundary conditions, defined as the fixation of nodes at the edges of the model, the water flow in various construction stages was also simulated. The initial water level was modeled on 38.5 m above sea level, as steady flow. Then, for the construction purposes, the water was drained through the dike (modeled as transient flow) to the ordinate of 36.1 m above sea level. After the construction, the water was refilled into its initial level, and once again, the flow was modeled as transient. In the final stage of the analysis, during the consolidation, the embankment was infiltrated with water of a transient flow, which eventually converged to the steady state [1, 12]. The reservoir's water level changes over time are shown in Figure 4.

On the opposite side of the embankment, "review" elements were incorporated, allowing for the free outflow of the water without affecting the boundary conditions of the seepage analysis. Additionally, the phenomenon of partial soil saturation was considered, utilizing Van Genuchten functions. These functions describe the relationships pertaining to flow of water in soil through analytical expressions that define soil water retention curves [6–9, 11].

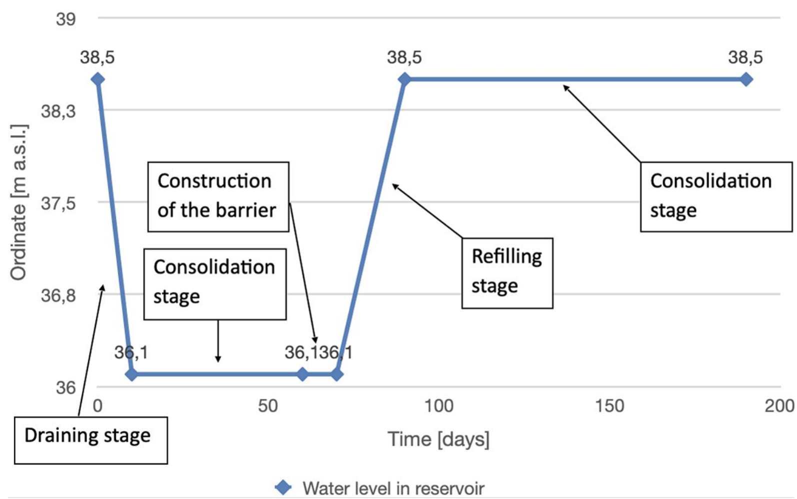

Fig. 4. Reservoir filling diagram with marked construction stages implemented in the software

3.4. Construction of the road and the cut-off wall

In the analysis, the existing road structure and anti-seepage barrier were modeled as isotropic elastic materials. The road structure was modeled using continuum elements, while the barrier was modeled using shell elements with cross-sectional characteristics [8, 10].

The primary purpose of the cut-off wall was only to cut off the groundwater flow and prevent it from infiltrating through the embankment. The choice of a vinyl sheet pile wall was based on its suitability for the design, offering advantages such as corrosion resistance, no chemical reactivity with soil and water, lightweight construction, and high durability.

During the initial phase, the road surface was loaded with a uniform pressure of 25 kN/m^2. The design solution required the bottom of the vinyl sheet wall to extend at least 1.0 meter into organic soils, which have a low water-permeability coefficient.

3.5. Construction phases

In the coupled analysis conducted for the project, the construction of the cut-off wall was divided into following construction phases:

1. Stage “0”:
2. Water level in the reservoir: 38.5 m a.s.l.,
3. Modeling mesh and boundary conditions,
4. Road Surface loading 25 kN/m^2.
5. Drainage stage (t = 10 days):
6. Lowering the water level using function of time 38.5 to 36.1 m a.s.l.,
7. Modeling transient water flow.
8. Consolidation stage (t = 50 days):
9. Stabilization of transient flow into a steady flow,

10. Embankment stability analysis using SRM method after lowering the water in the reservoir,
11. Cut-off wall construction (t = 10 days):
12. Construction of the vinyl sheet wall
13. Filling stage (t = 20 days):
14. Refilling the reservoir back to the initial ordinate of 38.5 m a.s.l., using function of time,
15. Embankment stability analysis using the SRM method after refilling the reservoir.
16. Consolidation stage (t = 100 days):
17. Further stabilization of transient flow, converging to a steady state,
18. Embankment stability analysis using SRM method after stabilization of groundwater conditions.

4. Results of the numerical analysis

4.1. Groundwater level

The calculations showed that with a high water level in the reservoir (38.5 m above sea level), the amount of groundwater seeping out on the downstream slope of the embankment reduced from approximately 2.5 m^3/day (per linear meter of the embankment) to 0.0 m^3/day after the construction of the cut-off wall.

Figure 5 shows the groundwater levels in each phase of the analysis: upper left corner represents stage “0” with high water damming level, the upper right corner shows draining stage with the lowered water level, lower left corner displays construction of the cut-off wall, and lower left corner depicts the beginning of the consolidation stage after execution of the cut-off wall.

Figure 6 shows the final water level, after the construction of the cut-off barrier and 100 days of consolidation processes.

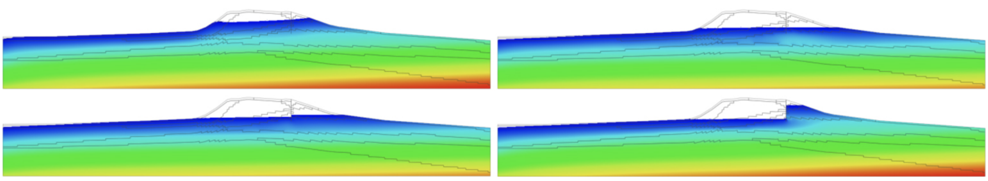

Fig. 5. Water level during various construction phases

The coupled analysis of stresses and filtration showed that the construction of the vinyl sheet pile wall, designed as a cut-off wall anchored in soils with low water permeability, effectively lowered the water level on the downstream slope of the embankment. Figure 7 displays the water level on the downstream slope of the embankment over time. After the construction and refilling of the reservoir, the water level on the analyzed side did not return to its original level. Figure 8 presents selected filtration paths after the final construction stage.

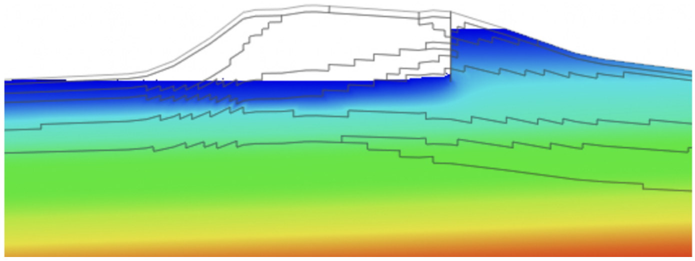

Fig. 6. Water level after final construction stage – consolidation lasting 100 days

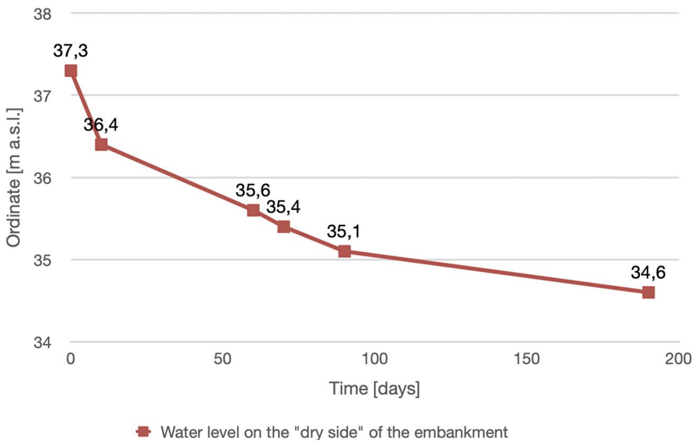

Fig. 7. Changes of the water level on the downstream slope of the embankment over time

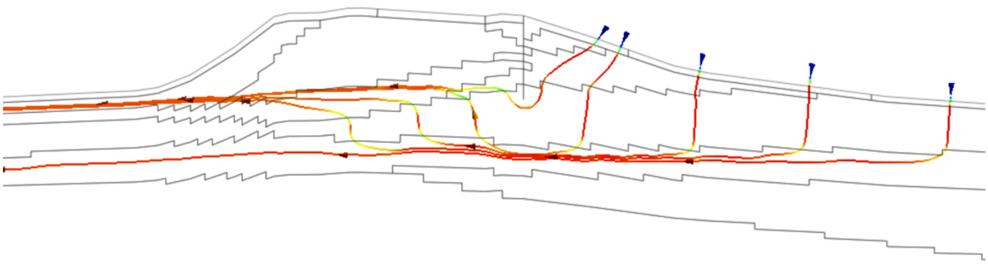

Fig. 8. Selected water flow paths – final stage

4.2. Displacements

The change in the groundwater level induces stress variations within the soil medium, resulting in embankment settlement (when the reservoir water level is lowered) or uplift (when the reservoir is filled). The analysis conducted indicated that lowering the water in the reservoir from 38.5 to 36.1 m above sea level leads to an embankment settlement of 19 mm. The analyzed embankment has previously experienced water level fluctuations several times; nevertheless, it is estimated that after the construction of the vinyl sheet pile wall, the embankment will permanently settle by approximately 22 mm. However, the upstream slope of the embankment will still undergo slight displacements depending on the water level in the reservoir. Furthermore, the permanent lowering of the water level in organic soils may cause secondary consolidation, which was not considered in the analysis due to its unpredictable nature, arising from the diversity of soil structures of organic soils. Figures 9– 12 illustrate displacements in various construction phases and Figure 13 shows the embankment displacements over time.

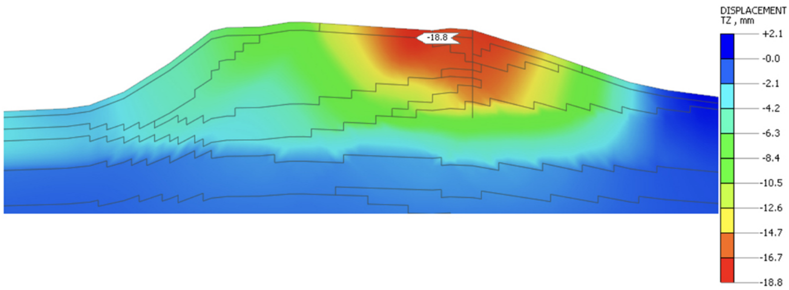

Fig. 9. Settlements – consolidation stage after dewatering, before the installation of the barrier

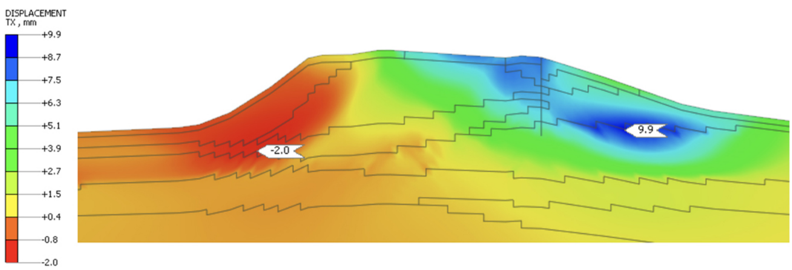

Fig. 10. Horizontal displacements – consolidation stage after dewatering, before the installation of the barrier

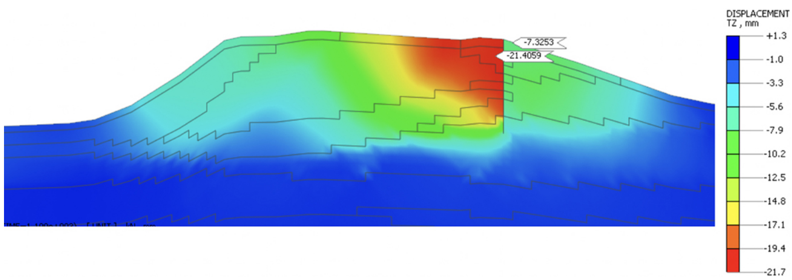

Fig. 11. Settlements – final stage

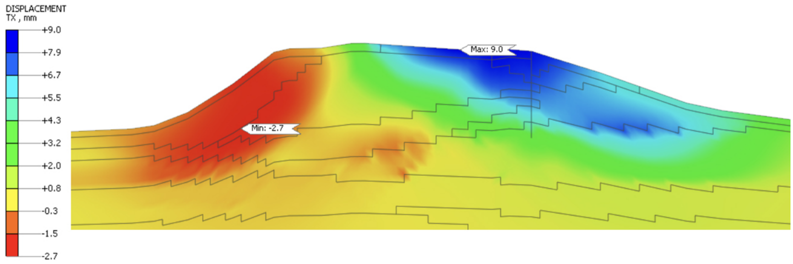

Fig. 12. Horizontal displacements – final stage

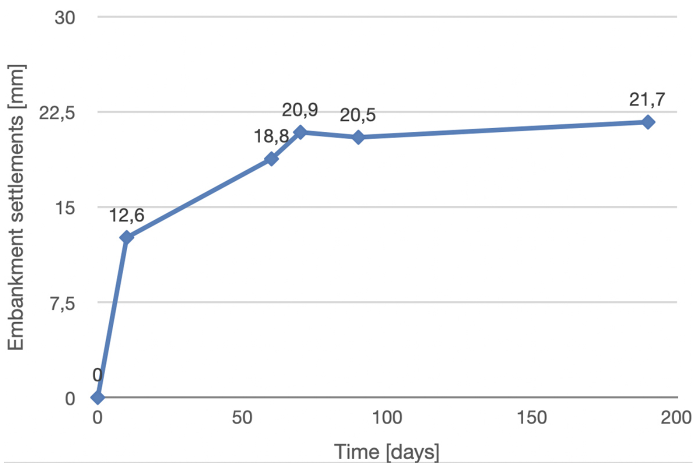

Fig. 13. Settlements of the embankment over time

4.3. Stability of the slope

The additional aim of the numerical analysis was to assess the stability of the embankment in various construction phases without considering the concept improvement in case of instability. The analysis revealed low safety factors, making it impossible to claim that the slope is stable, regardless of the construction stage:

– 1.06 in stage "0",
– 1.03 after lowering the water level in reservoir to 36.1 meters above sea level,
– 1.10 after construction of the cut-off wall and filling the water in reservoir.

According to Wysokiński criterion [15], a factor of safety of at least 1.25 is required to consider the slope safe from landslides. The analysis indicates that the construction of the barrier will not worsen the slope stability. It should also be emphasized that in the current state, slope stability is already at risk. The slip surface after dewatering would be global, potentially leading to damage to the road structure. The strain results indicating potential slip surfaces were presented in Figures 14 and 15.

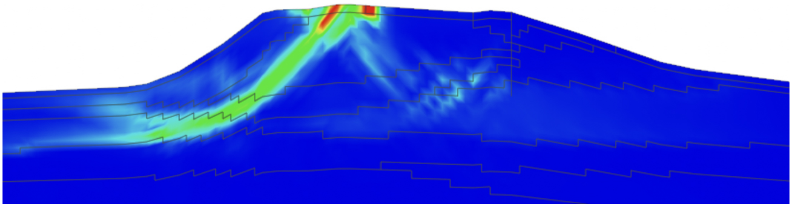

Fig. 14. Strains – stage “0”

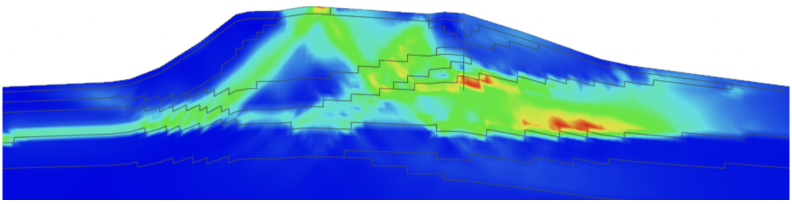

Fig. 15. dewatering stage before the construction of the cut-off wall

5. Conclusions

The coupled analysis utilizing the finite element method enabled the calculation of settlement and embankment stability, as well as the examination of water flow paths in various construction stages. The use of a polyvinyl chloride sheet pile wall anchored in organic soils with low permeability coefficient successfully served as a cut-off wall, safeguarding the road embankment from adverse water infiltration from the reservoir. Draining and refilling of the reservoir lead to embankment settlement, with the maximum value reaching approximately 22 mm after the construction of the cut-off wall and consolidation process. According to regulations, settlement value in slopes should not exceed 10 cm [14].

However, the stability of the embankment itself remains an unresolved issue. After the construction of the wall and refilling of the reservoir, the factor of safety reaches 1.10. This value categorizes the slope as potentially susceptible to landslides – as per the regulations of the Ministry of Transport, Construction and Maritime Economy [14], the safety factor should be greater than 1.50. The primary objective of the analysis was to prevent water exudates on the downstream slope of the embankment, and the enhancement of stability may be contemplated in the future. It is essential to note the historical construction of the embankment, whose material would currently be deemed unsuitable for construction purposes. Moreover, the man-made soil was uncompacted, as confirmed in the documentation [2].

In the future, the issue of reinforcing the embankment to improve its stability will depend on the investor’s decision regarding the duration of road closure, as both directions are feasible: those involving the dismantling of the embankment structure and its reconstruction, as well as non-invasive methods potentially expediting the construction process. Solutions involving the reconstruction of the embankment would entail its reconstruction using lightweight fill such as styrofoam or expanded clay aggregate [16], aimed at minimizing stress on compressible organic soil layers, or the implementation of gravel columns extending to the layer of sand beneath the organic soil layer [17]. These would serve as vertical filtration paths and additionally reinforce the effect of limiting horizontal water flow through the embankment.

Among the non-invasive or partially non-invasive methods are injection methods, such as low-pressure grouting [18], geopolymer injections [19], or solidification [20], followed by the execution of only a modernized pavement and roadbed, for example utilizing the MCE technology, whereby the existing pavement would serve as a recycled roadbed layer for the new road [21].

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Ocena ryzyka niestabilności nasypu drogowego pod wpływem filtracji wody za pomocą w pełni sprzężonej analizy numerycznej

Słowa kluczowe: Przesłona przeciwfiltracyjna, MES, stateczność skarpy, nasyp drogowy, ścianka szczelna

Streszczenie:

Przesłony przeciwfiltracyjne budowli ziemnych stanowią istotny element geotechniki, a zakres dostępnych technologii ograniczających przepływ wody stale się poszerza. Ścianki szczelne wykonane z polichlorku winylu (PVC) zyskują na popularności oraz stanowią coraz częstszy wybór projektantów, pomimo wieloletniego stosowania ich w swojej tradycyjnej stalowej formie. Niniejszy artykuł przedstawia studium przypadku nasypu drogowego drogi wojewódzkiej nr 181 w miejscowości Drawski Młyn. Przedstawiono kontekst historyczny, opisano warunki gruntowo-wodne oraz przeprowadzono obszerną analizę filtracji przez nasyp w różnych etapach budowy przy użyciu metody elementów skończonych. W artykule zaprezentowano trójwymiarowy model numeryczny, na którym wykonano w pełni sprzężoną analizę naprężeń i przepływu. Wyniki zawarte w publikacji obejmują ścieżki przepływu wody przez nasyp, stateczności skarpy oraz przemieszczenia przed i po wykonaniu przesłony, przedstawiając nowoczesne i ekologiczne rozwiązanie tego problemu inżynierskiego.

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