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ASSESSMENT OF THE FILTRATION STABILITY OF THE FLOOD CONTROL LEVEE ON THE LITTLE DANUBE

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Abstract

Some of the accompanying phenomena of climate change that have been documented include extreme hydrological events. These significantly influence the hydrological regime of river basins, leading to more frequent occurrences of hydrological extremes such as floods and periods of drought (Melo et al., 2012, Svoboda et al., 2000). Long-term drought periods highlight the urgency of constructing water structures to create large-capacity artificial reservoirs to ensure water supplies during periods of scarcity. Intense short-term rainfall events underscore the increased need for flood control measures. Flood control levees are a significant component of flood control measures (Kotaška and Říha, 2023). Many of them, such as the Danube flood control levees, whose construction dates back to the reign of Maria Theresa (Pekárová et al., 2013; Halmová and Pekárová, P 2020), have been in operation for centuries. Considering their age, the long-term impact of hydrodynamic loading, as well as changing conditions, including hydrological, morphological, geological factors, etc., these water structures require attention. They include the right-bank flood control levee of the Little Danube River. This paper focuses on an analysis of the risk factors for the filtration stability of the levees's subsoil under extreme hydrodynamic loading and the methodological approach applied in optimizing planned measures.

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Key words

- Flood control levee,
- Safety,
- Hydrodynamic loading,
- Suffusion,
- Filtration stability.

1 INTRODUCTION

The safety of water structures, especially earth-fill levees, is significantly determined by the properties of the geological environment in which they are located, especially for flood control levees. Considering that flood control levees are usually of a low height, i.e., around 3 to 5 m, they are often built as homogeneous levees from local materials. In addition to the uncertainty of hydrological data, which creates a risk of the overflow of levees, seepage is one of the most common causes of their failure and accidents. Seepage can be activated in the body of a levee (if its quality does not meet the requirements of homogeneous levees), but also in the subsoil. Their typical accompanying features include, for example, the occurrence of wet areas or springs at the base of the downstream slope, or in its immediate vicinity, sometimes accompanied by the suffusion driven out of fine-grained particles from the subsoil, the breaking of low-permeability cover layers by uplift pressure, etc. (Fig. 1).

Fig. 1 *Accompanying phenomena caused by seepage through the subsoil of the left-side flood control levee of the Danube during flood flows in 2002 (source: Archive of VV Bratislava, TBD Department)*

Geological and geotechnical conditions of the area affected play an important role in the amount of these undesired phenomena. Experience confirms that problems with flood control levees, where phenomena endangering their safety have occurred in recent decades, have usually been related to the geological composition of their subsoil. Usually, the occurrence of permeable gravelly and sandy soils in the subsoil is susceptible to suffusion. Examples in Slovakia include some sections of the left-bank flood control levees of the Morava River, the flood control levees of the Váh, Hron, and Latorica rivers, and others (Lukáč and Bednárová, 2006).

The flood control levees of the Danube River are characterized by special geological conditions, where the occurrence of permeable gravelly and sandy soils reaches extreme depths, i.e., more than 300 m in the Gabčíkovo area. The flood control levees of the Little Danube River, which are the subject of this paper, also belong to this geologically and hydrogeological specific area (Fig. 2).

Fig. 2 *Layout of exploratory boreholes TV-1 to TV-20 on the right-hand side of the levee of the Little Danube between the Kolárovo and Aszód pumping stations, which shows the occurrence of surface leaks during the flood flows in 2006*

2 MAIN PROPERTIES OF THE LEVEE AND ITS SUBSOIL

The right-bank flood control levee of the Little Danube (hereinafter referred to as the "RL") in the section studied between the pumping stations of Aszód and Kolárovo is 10.92 km long (Fig. 2). Its height ranges from about 3 to 5 m above the foundation level or about 3 to 4 m above the terrain. The proposed elevation of the crest of the levee to be reconstructed is 114.00 m a.s.l.; its width is 4.0 m; and the upstream and downstream slopes are 1:2. The current elevation of the crest of the levee in the section studied is about 15 - 25 cm below a level of 114.0 m a.s.l. The slopes are different: on the upstream side, it is usually 1:2, and on the downstream side, it is 1:2; at higher heights of the levee, the slopes are gentler than in the lower part. The area of interest in which the levee is located is part of the lower Žitný Island, which is covered by quaternary fluvial sediments. The quaternary sediments mainly consist of fine to medium-grained sands with admixtures of fine gravels, which alternate with layers of heavily sandy clays or, less frequently, silty clays. The maximum thickness of these sediments is 110 m.

The detailed geological structure of the RL subsoil from Aszód to Kolárovo, with a length of 10.92 km can be seen in a geological and hydrogeological survey (Kminiaková et al., 2018). The body of the levee mainly consists of clays with a medium-to-high plasticity and a stiff and locally soft consistency. In some places strays were also found in the body of the levee, e.g., silty sands, sands with admixtures of fine-grained soil, or even more continuous layers of sandy non-cohesive soils.

The surface layers of the levee's foundation are formed by clayey to silty-clayey soils, and are underlain by silty and clayey sands, the thickness of which ranges from about 1.5-2 m to 3.9 m in the section studied. The sandy-clayey surface soils gradually pass into non-cohesive sediments, i.e., sands and gravels, mainly of sandy fractions. Poorly sorted sands, which are mainly medium to well-compacted, are dominant. The occurrence of gravelly soils was observed only sporadically in the section studied. Poorly sorted sands and gravels are the dominant collectors of the groundwater's movement.

3 ASSESSMENT OF THE FILTRATION STABILITY OF THE FLOOD CONTROL LEVEE

Among the characteristic risk factors related to the assessment of the filtration stability of flood control levees located on permeable subsoil with low-permeable cover layers are their uplift failure and internal suffusion. Both of these risk factors are determined by the geological structure of the subsoil and hydrological conditions. These were determined locally based on the course of the flood wave in 2006 in the area studied (Mišík, M. et al., 2018). With its duration of 14 days, the water level in the Little Danube riverbed reached a level above 113 m a.s.l. after about 7 days (Fig. 3)

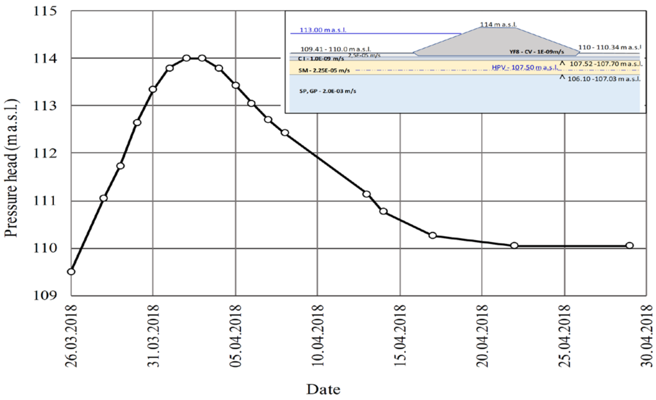

Fig. 3 *Development of the water level of the Little Danube at the mouth of the Klatovské branch: input for the numerical model*

The analysis of the grain size composition of the permeable sandy and gravelly soils in the levee's subsoil showed their susceptibility to suffusion. Under hydrodynamic loading in the conditions of the RL, the hydraulic criterion according to Hálek (Hálek and Švec, 1979) and Istomina (Istomina, 1957) of Ikrit = 0.2 was recommended for assessing the filtration stability of the soils for internal suffusion (Fig. 4).

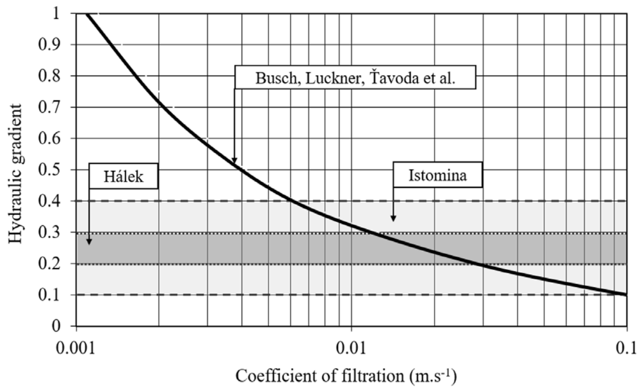

Fig. 4 *Criteria for filtration stability according to Istomina; Hálek; Busch; Luckner, etc.*

3.1 Methods

The SEEP/W module Geo-Studio program (GEO-SLOPE, 2015) was applied to solve the filtration tasks presented related to the assessment of the filtration stability of the soils in the body and subsoil of the RL. The choice of this program, which uses the finite element method, was based on the nature of the task, which requires an analysis of the development of the filtration movement through the body and subsoil of the flood control levee under extreme hydrodynamic loading, i.e., during flood flows. From a theoretical point of view, this is a transient task.

The mathematical solutions of filtration tasks are based on a continuity equation and Darcy's filtration law. Due to their complexity, spatial tasks are often replaced by solutions on the horizontal and vertical planes, if they do not violate the physical essence of the phenomenon (Thomas and Yuan, 1996). When approximating with a plane model, the solution follows from the equation (Fredlund and Rahardjo, 1993):

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = m_w \gamma_w \frac{\partial H}{\partial t} \qquad (1)$$

where H the total head
k_x, k_y the hydraulic conductivity in the direction of the x, y a
m_w the slope of the storage curve
γ_w the unit weight of the water
Q the boundary flux applied
t time

The uniqueness of the solution of equation (1) is given by the boundary conditions of the flow area solved and the initial conditions. A detailed description of the solution using the finite element method can be found in the literature (Kazda, 1997).

3.2 Approach to the solution

Under the existing conditions of the RL, and due to the smaller extent of its height above the terrain (approx. 3.5 m - 4 m) and the relatively homogeneous geological composition of its subsoil, it was possible to analyze the effect of extreme hydrodynamic loading on the development of the groundwater and seepage flow parameters in the form of a parametric study. The calculations were performed on a cross-section of the levee representing the existing conditions, i.e., the height of the levee and the geological composition of its subsoil, so that the results of the solution would be on the safe side. The parametric study aimed to analyze the effect of the distance of the Little Danube riverbed from the levee's body on the development of filtration parameters in its foundation under extreme hydrodynamic loading (Bednárová and Grambličková, 2018). A schematic diagram, which characterizes all the important parameters of the profiles solved in the section studied, is presented in Fig. 5.

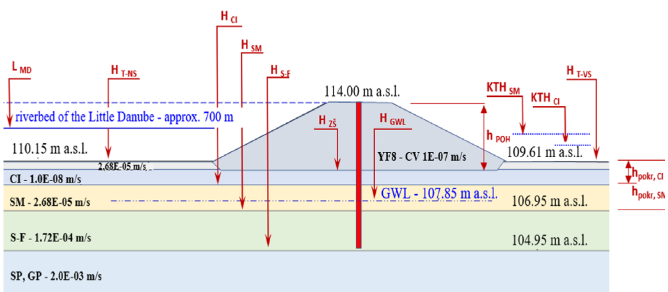

Fig. 5 *Scheme representing the parameters of the right-hand side of the levee, which were used in the numerical analysis*

Where:

LMD	distance of the Little Danube from the toe of the right-bank flood control levee (m)
$H_{zš}$	level of the foundation base of the flood control levee (m a. .l.)
H_{GWL}	groundwater level (m a.s.l.), which is directly related to the initial water level in the Little Danube; it forms the initial boundary condition in the numerical modeling
h_{POH}	height of the flood control levee above the foundation (m)
H_{CI}, H_{SM}, $H_{S\text{-}F}$	levels of the lower boundary of the clay cover layer (CI), silty sands (SM), sands with admixtures of fine-grained particles (S-F) (m a.s.l.)
$H_{T\text{-}NS}$, $H_{T\text{-}VS}$	level of the terrain on the upstream (T-NS) and downstream (T-VS) of the flood control levee (m a.s.l.)
h_{pokr},CI	thickness of the cover layer formed by the clay soil (m)
h_{pokr},SM	thickness of the cover layer formed by the clay soil and silty sands (m)
KTH_{CI}	level of the critical pressure horizon corresponding to the CI cover layer (m a.s.l.)
KTH_{SM}	level of the critical pressure horizon corresponding to the CI and SM cover layer (m a.s.l.)

Within the analysis focused on the development of the filtration parameters of the groundwater and seepage flows under extreme hydrodynamic loading, attention was focused on:

- The hydraulic gradients in the levee subsoil, which are important for assessing the risk of internal erosion (suffusion).
- The uplift forces on the lower interface of the low-permeability cover layers, which are crucial for assessing the risk of their rupture.
- The risk of the emergence of springs and waterlogging of the toe of the downstream slope, the occurrence of which would negatively affect its structural stability.

The depth of the cut-off wall (COW) was chosen in the basic calculations to seal any preferential seepage paths through the body of the levee or in the area of its foundation base, considering its connection to the underlying cover layers. The numerical analysis was also performed without considering the COW.

Respecting the different geological compositions of the levee subsoil in some of its profiles within the 10.92 km section studied, the analysis of the effect of extreme hydrodynamic loading on the development of the filtration parameters of the groundwater and seepage flows was separately performed.

3.3 Mathematical model

With approximately the same levee parameters (height above terrain from about 3.5 m to 4 m) and a relatively homogeneous geological composition of its foundation in the set of profiles analyzed (18 in total), a numerical model was constructed to represent the least favorable conditions (Fig. 6). This means that any other conditions within the solved profiles, as determined by a more favorable geological composition of the levee subsoil and its parameters, were on the safe side with regard to an analysis of the possible risk factors.
Focused on assessing the filtration stability of its body and foundation resulting from the geological survey (Kminiaková et al., 2018), the parametric study considered the average permeability coefficients of the individual soils as follows:

- clay soils in the levee's body and in the cover layer: $k_{f,C} = 1.0\times10^{-9}$ m.s^{-1}
- silty sands (SM) in the foundation: $k_{f,SM} = 2.25\times10^{-5}$ m.s^{-1}
- poorly-graded sands (SP): $k_{f,SP} = 2\times10^{-3}$ m.s^{-1}
- cut-off wall of 10 m: $k_{f,PTS} = 1.0\times10^{-7}$ m.s^{-1}
- Thickness of the surface's cover layer to the lower boundary of the clays: 2.3 m
- Thickness of the cover layer to the lower boundary of the silty sands (CH, CI+SM): 3 m

The essence of the study was to analyze the effect of extreme hydrodynamic loading on the parameters of the filtration flow under the conditions of the levee, assuming the position of the Little Danube River's flow from its body at distances of 30, 80, 100 and 150 m.

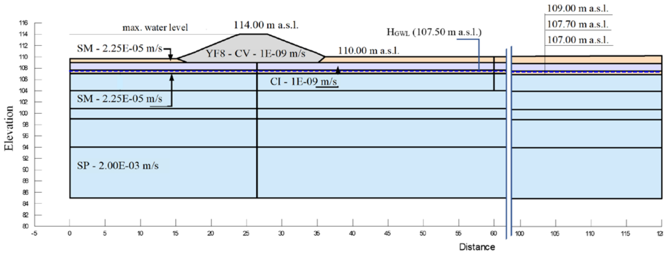

Fig. 6 *Numerical model representing the most unfavorable conditions of the levee in profiles from TV-1 to TV-17 and TV-19 without a cut-off wall*

3.4 Illustration of the results of the numerical solution

3.4.1 Hydraulic gradients in the subsoil of the levee

The results of the geological survey in the area studied confirm the presence of silty sands and poorly sorted sands in the subsurface layers (Figs. 5 and 6). When accepting the hydraulic criterion recommended by Istomina as $I_{krit} = 0.2$ for the risk of internal suffusion (erosion) in sandy soils, it follows in the entire profile of the subsoil layers, in both the silty sands (SM) and poorly sorted sands and in all the locations examined along the Little Danube riverbank from the flood control levee, that the maximum hydraulic gradient remains below the recommended critical value of 0.2 (Fig. 7).

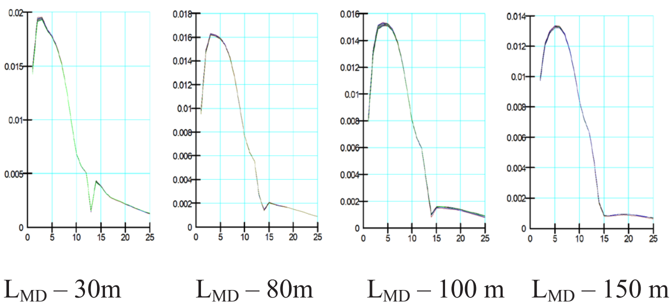

Fig. 7 *Development of the hydraulic gradients in the subsoil of the flood control levee at different distances between the riverbed of the Little Danube and the axis of the levee*

3.4.2 Uplift

The shallow, low-permeability cover layers (CH, CI) reach a thickness of 2.3 m in the representative profile, which corresponds to a critical pressure horizon of 111.84 m a.s.l. at a ground surface level of 110 m a.s.l. Considering the silty sands as part of the low-permeability cover layers, their thickness is 3 m, and the corresponding critical pressure horizon (CPH) is at 112.13 m a.s.l. From the course of the uplifts (piezometric heights) calculated under the extreme hydrodynamic loading (Fig. 8) acting on the lower interface of the cover layer (SM), it follows that the critical pressure horizon of 112.13 m a.s.l. would be exceeded under the conditions assumed by the numerical model, except for the alternative position of the Little Danube riverbed from the levee at a distance of more than about 150 m.

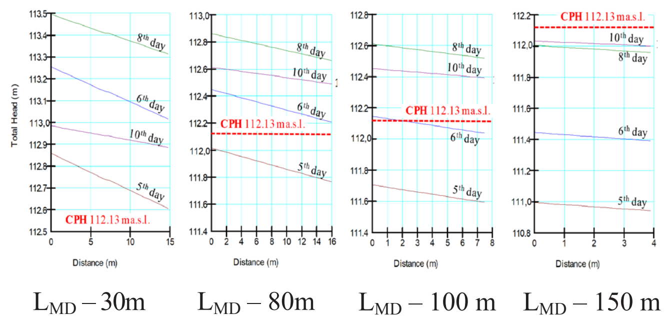

Fig. 8 *Development of uplift (piezometric heights) at the bottom boundary of the covering layers at different distances between the riverbed of the Little Danube and the axis of the levee*

3.4.3 The risk of the occurrence of seepage and saturation of the upstream slope toe

Assuming the presence of quasi-impermeable clay cover layers at an elevation of 107.70 m a.s.l., the risk factors of the occurrence of seepage and saturation of the upstream slope toe were not demonstrated in any of the alternatives examined through numerical modeling. The results achieved indicate that, hypothetically, in the modeled assumptions of the flood control levee, at distances ranging from 30 to 100 meters from the Little Danube River, there exists a risk of the violation of the filtration stability of the levee's body and its subsoil by the failure of the cover layers due to uplift. In such conditions, an effective remedial measure is a stabilization backfill. It is noted that the results presented are valid both when assuming the filtration regime without seepage cut-off walls and when modeling them through the levee's body. The determining factor for the same results lies in the permeability coefficients for the clays (10^{-9}m.s^{-1}) and COW (10^{-7} m.s^{-1}).

3.5 Results of the parametric study

For a levee with a height of 4 m and a crown width of 4 m, the results of the parametric study analyzing the effect of extreme hydrodynamic loading on the development of hydraulic gradients, uplift, and seepage in the subsoil of the flood control levee (RL) in the section surveyed (according to Fig. 5), include:

- nomograms representing the values of the uplift pressure on the surface cover layers of the levee's subsoil; the position of the levee's downstream toe from its axis (L) is displayed on the horizontal axis. For a slope of 1:2, its position is L = 10 m, and for a slope of 1:3, its position is L = 14 m, etc. The position of the Little Danube riverbed from the levee's axis ranges from L_{MD} = 30 m (red line) to L_{MD} = 150 m (green line). The in-between values (L_{MD} = 40 m, 50 m, etc.) are indicated by dashed lines (Fig. 9),
- dependence of the development of uplift pressure in the area of the levee's downstream toe on the changing distance of the Little Dunaj River channel from the levee's axis L_{MD} (Fig. 10); The blue line (L = 10 m) applies to a slope of 1:2 and the red line (L = 11 m) to 1:2.25,
- dependence of the development of the maximum hydraulic gradients in the sandy soils of the levee's subsoil on the changing distance of the Little Danube riverbed from its axis LMD (Fig. 11);

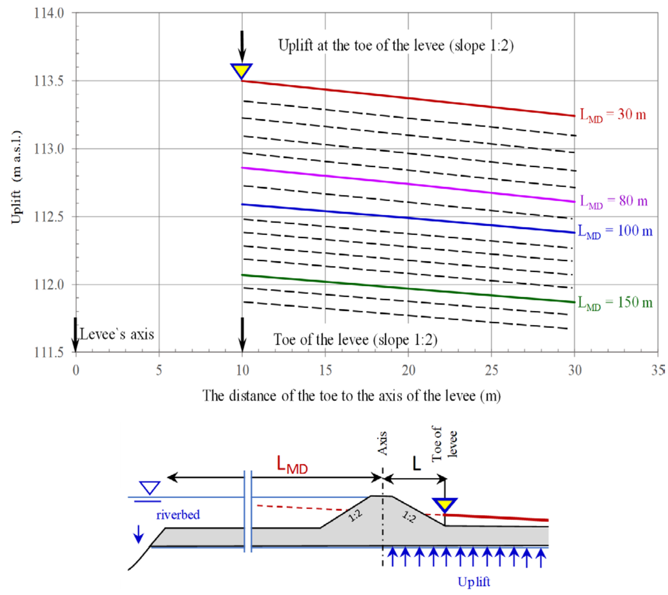

Fig. 9 *Nomograms for determination of the uplift to cover the layers in the location of the levee's downstream toe*

The solution results, which are presented in the form of the nomograms provided, were applicable in assessing the criteria monitored in the individual profiles of the flood control levee, taking into account their specificities. The hydraulic gradients, uplift on the cover layers, and saturation of the toe of the downstream slope could be appropriately assigned to each profile based on the position of the flow from the levee's body within a range of 30m to 150m, while also considering the changing thickness of the cover layers. This is because the level of their boundary and the underlying permeable aquifer layers remain almost constant (approximately 107.0 m a.s.l.).

It is evident from the nomograms that the uplift pressure on the cover layer decreases with the increasing distance of the Little Danube River from the body of the levee. Under the given hydrological conditions (7-day flood wave) and geological composition of the levee subsoil, it can be assumed that the pressure horizon at the toe of the slope will decrease below 112.0 m a.s.l. for a stream position greater than 150 m. This is also supported by the results presented in Figure 10, which shows two dependencies:

- The blue line corresponds to the toe of the downstream slope at a distance of 10 m from its axis (with a slope of 1:2 and a crown width of 4 m).
- The red line can be applied when the downstream slope is gentler and the toe is at a distance of approximately 11 m from the axis of the levee.

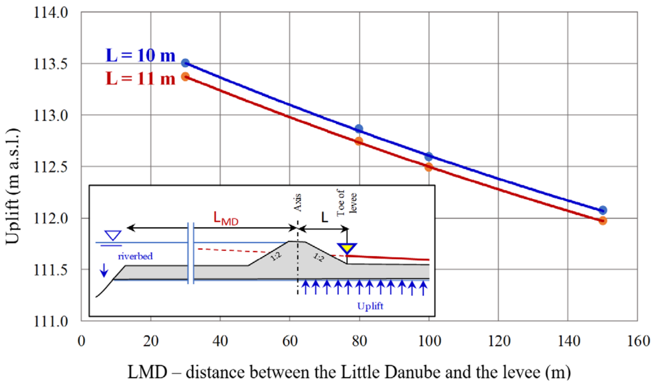

Fig. 10 *Dependency of the pressure horizon of the levee's downstream toe on the distance of the Little Danube*

In Figure 11, the dependence of the hydraulic gradients on the position of the Little Danube in the subsoil beneath the downstream toe of the flood control levee is depicted. From the results, it can be inferred that the values achieved are negligible in the geological, hydrogeological, and hydrological conditions examined, as they are well below the critical value of I_{krit}= 0.2.

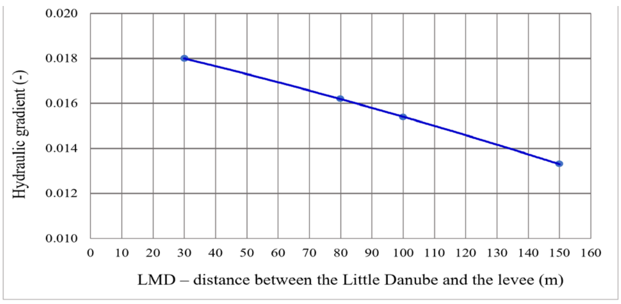

Fig. 11 *Dependency of the hydraulic gradients in the sandy layered subsoil*

Based on the results of the parametric study, it was possible to determine the values of the pressure heads assumed in the examined profiles of the right-bank flood control levee of the Little Danube under extreme hydrodynamic loading. These values varied not only due to the morphological factors (position of the levee from the Little Danube riverbed) but also due to the geological conditions (differences in the thickness of the cover layers). Consequently, remedial measures could be proposed to address these changing conditions.

4 CONCLUSION

Optimizing remedial measures for flood control levees is an exceptionally significant and complex task. Utilizing numerical modeling can significantly contribute to an efficient and economical solution to this problem. However, the reliability of the results obtained depends on the reliability of the geological and hydrogeological survey and the hydrological data. In recent years, remediation using cut-off walls has become prominent. Extensive experience from assessing the filtration stability of flood control levees has led to the realization that a cut-off wall that is anchored in quasi-impermeable subsoil (in the case of shallow permeable soils in their subsoil) can indeed eliminate the risk of internal suffusion and the failure of cover layers due to extreme hydrodynamic loading. However, under normal loading conditions, such a solution poses the risk of communication between the flow and the groundwater of the affected environment. Therefore, such a solution must be carefully considered. In cases of the substantial thickness of permeable gravelly or sandy soils, a so-called "suspended" cut-off wall is typically recommended. By lengthening the seepage path, the desired reduction in hydraulic gradients can be achieved, but the risk of failure of the cover layer due to exceeding the critical pressure head may not be eliminated by this type of cut-off wall. In such cases, a stabilization backfill or a relief drainage system is a more effective measure.

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