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APPLICATION OF THE FILTRATION NUMERICAL MODEL FOR THE ASSESSMENT OF THE EFFECTIVENESS CUT OFF WALLS IN LEVEES

ZASTOSOWANIE NUMERYCZNEGO MODELU FILTRACJI DO OCENY EFEKTYWNOŚCI PRZESŁON HYDROIZOLACYJNYCH W WAŁACH PRZECIWPOWODZIOWYCH

A b s t r a c t

In this paper, a two-dimensional numerical model of filtration was used to evaluate the effectiveness of cut off walls constructed in DSM and WIPS technology. Numerical calculations were performed for a steady state water flow through the body and the base of the levee. On the basis of these simulations results, an assessment of the effectiveness of these cut off walls was made.

Keywords: cut off walls, levee, FEM

S t r e s z c z e n i e

W artykule do oceny efektywności przesłon hydroizolacyjnych wykonywanych w technologii DSM i WIPS zastosowano dwuwymiarowy numeryczny model filtracji przez korpus i podłoże obwałowania. Obliczenia numeryczne wykonano dla stanu przepływu ustalonego wody przez korpus i podłoże wału. Na podstawie wyników symulacji dokonano oceny efektywności tych przesłon.

Słowa kluczowe: przesłona hydroizolacyjna, wał przeciwpowodziowy, MES

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1. Introduction

The purpose of levees is protecting the adjacent areas from flooding. The geometry and soil configuration of the levee must be properly selected so that the structure is safe in terms of stability and filtration. Proper levee construction should take into account the correct height, preventing overflowing during peak flows and considering wave accumulation caused by wind or embolic events (e.g. freezing). One of the hydraulic conditions for levees, which should always be met, is preventing the free flow of water on the downstream slope. Unfavorable soil configuration in the levee's cross section when a permeable soil (e.g. sand) is placed on the upstream side and a poorly permeable soil (e.g. clay or clayey sand) on the downstream slope causes an increase in hydraulic pressure inside a levees body. During intensive and long-lasting floods, this state enables the formation of leaks on the downstream slope. A high level of water pressure inside the levee's body can cause dangerous suffosive outflows. This phenomenon may appear on the downstream slope, at the toe, or in the adjacent area. The long term persistence of such a state can therefore lead a levee to break. Considering stability and proper filtration, it is preferred that the full saturation area of the levee's body was as small as possible and located as low as possible. It is assumed that the water table should not be closer to the downstream slope than 1 m, this can be achieved by means of appropriate drainage systems [1]. The important matter is the height of water pressure in the base. During flood events, the most beneficial is the water pressure distribution to be similar to the conditions found before this period, i.e. approximate to the natural conditions.

One of the methods to repair levees is to form vertical cut off walls along their body, eliminating or reducing unwanted water filtration and increasing the stability of levees. These diaphragms are created through various methods using special hardening mineral slurries. These are primarily sheet piling in narrow trenches, vibration-grouting slit diaphragms (WIPS) and the palisade of deep-mixed soil columns (DSM).

Filtration analysis in levees should be considered using an unsteady state water flow model in porous media, because its course mainly depends on the time-varying wave hydrograph of a river. [4–5]. In recent years, both in the Vistula and the Oder catchment area, there has been an increase of long-lasting floods distinctive by two peak points several days apart [2–3]. This situation causes a long lasting high water saturation of the levee. Under these hydrological conditions, the effectiveness of cut off walls may be analysed in steady state conditions resulting from a long-lasting high water level in the river. The research was performed on a selected section of the right Warta River levee located in the village of Kostrzyń.

2. The study area

2.1. Specification of the selected section of the levee

A generalized cross-section of the levee was assumed for the purpose of model studies. The most unfavorable was considered to be the one with the smallest width of the base with the following parameters: height 3.20 m, width 28.60 m. The levee has no drainage facilities and did not have any cut off facilities until this project.

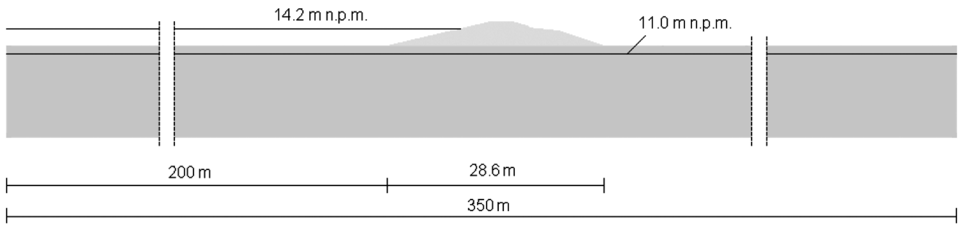

Fig. 1. Filtration area outline

The average distance between the levee and Warta River in this area is about 200 m. The elevations on both sides of the levee vary between 11.5 and 13.0 m a.s.l. In the immediate vicinity of the levee it is about 12 m a.s.l. During the geotechnical investigations, where the maximum drilling depth amounted to 10 m, the impermeable layer was not found. According to the Polish Hydrogeological Atlas of 1993 [5] on a scale of 1:500 000 the depth of a first aquifer in the vicinity of Kostrzyń is up to 15 m. The filtration model assumes that the impermeable layer is at elevation 0 m a.s.l. The elevation of the groundwater table at the start of the flood is 11 m a.s.l., which is 1 m below the surface, and the maximum flood level is at elevation 14.2 m a.s.l., which is 1 m below the levee's crest. The total length of the filtration area is 350 m (Fig. 1).

The conducted geotechnical investigation has shown that the study area consists of accumulation of river. These are predominantly fine sands with inclusions of sandy silt with an organic content in the range of 5 to 15%. Through these materials, water filtrates in numerous places. As a result of these studies three, geotechnical layers were marked out:
– I – constructional embankment, which consists of the levee body,
– II – sands representing the aquifer,
– III – silty sands interbedding the aquifier.

The values of hydraulic conductivity for each layer and for the materials forming cut off walls were obtained from geotechnical investigations and are shown in If it is necessary to strengthen the levee and improve its filtration properties, a popular solution is to create vertical cut off walls. These are primarily sheet piling in narrow trenches, vibration-grouting slit diaphragms (WIPS) and the palisade of deep-mixed soil columns (DSM) [6].
Table 1 [6].

Three different stratifications were distinguished for the examined levee based on geotechnical documentation, all with a homogeneus body but a slighty different foundation:
– KP – homogeneus sands disregarding the silty inclusions considering their mild effect on the formation of the groundwater head;
– KPHI – homogeneous aquifer with a 0.5 m layer of silty sands lying directly beneath the surface;
– KPHII – homogeneous aquifer with a layer of silty sediments 20 m wide with a maximum depth of 1 m located centrally with respect to the embankment crest.

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Table 1

The values of hydraulic conductivity

Layer	hydraulic conductivity [m/s]
Constructional embankment [I]	6.0E–05
Aquifer [II]	1.5E–05
Silty sands [III]	4.0E–07
Cut off wall – DSM	4.0E–08
Cut off wall – WIPS	6.0E–10

2.2. Cut off walls

A variation of the method of implementation of diaphragm walls is the WIPS technology, which is based on forming a narrow trench (usually not wider than 20 cm) by inserting with vibrations a steel profile provided with nozzles on the bottom for applying a hardening slurry. After achieving the desired depth, the profile is pulled upwards with the simultaneous administration of adhesive, which fills the gap. The continuity of the diaphragm is obtained by performing successive plunging of the profile, partially overlapping. Once the adhesive hardens, the parameters of the obtained diaphragm are similar to the walls constructed in narrow trenches. In both cases, the advantage is the applicability in soils with organic content, due to the lack of mixing of the adhesive with the surrounding soil and groundwater.

Cut off walls using the DSM technology are constructed using drills equipped with mixers shaped as plate augers with nozzles for the mineral adhesive application. The process involves mechanical drilling without excavation, with the simultaneous administration of the adhesive. After achieving a desired depth, the soil is then mixed several times with the adhesive by repetitive raising and penetration. This results in a formation of a pile made of soil particles permanently combined with the hardened adhesive. By carrying out subsequent, partly overlapping piles, a continuous diaphragm is obtained with the parameters dependent on the adhesive used. This method works well in ground improvement by using cemented piles. In the case of cut off walls where excessive rigidity of the piles is not desired, clay or loam instead of cement is used as a base for slurries. Its efficiency is then dependent on the type and the physico-chemical properties of the soil that is to be treated. A significant disadvantage of the DSM method is the difficulty of maintaining proper vertical drilling at greater depths, which may lead to a lack of continuity of the diaphragm in the lower part.

A finished diaphragm, regardless of the implementation method, should have a hydraulic conductivity of about 10-7÷10-10 m/s, dissolving resistance to water and compressive strength not exceeding 1 MPa, so that the material retains sufficient flexibility to guarantee good cooperation with deformations in the ground. Therefore, adhesives based on loam are preferred with a small addition of cement as a binder.

3. Methodology

The GMS/SEEP2D numerical modeling system was used in the flow calculation through a cross-section of the river levee. This software was developed to model a variety of problems involving steady state of seepage [8]. The SEEP2D model is based on the following equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}+K_{xy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}+K_{yx}\frac{\partial h}{\partial x}\right)=0 \tag{1}$$

where:

h – total head (elevation head plus pressure head),

K – hydraulic conductivity.

The following conditions can be modeled using SEEP2D: isotropic and anisotropic soil properties; confined and unconfined flow for profile models; saturated/unsaturated flow for unconfined profile models; confined flow for plan (areal) models; flow simulation in the saturated and unsaturated zones; heterogeneous soil conditions; axisymmetric models such as flow from a well; drains.

In the model, a finite element method (FEM) is used for solving the governing equation (1) and the region being modeled is represented by a finite element mesh. Boundary conditions are typically entered as constant head at the node, the head equals the elevation (exit face) at a node, or as an incoming flux at a node or along an element edge. Exit face boundary conditions are used when modeling unconfined flow problems and should be placed along the face where the free surface is likely to exit the model. The SEEP2D program can calculate the head, flow, discharge (Darcian) velocity, and pore pressure at every node in the mesh.

In the elaborated model, an unconfined flow through a levee is simulated as a flow in both the saturated and unsaturated zones with isotropic soil properties. The hydraulic conductivity in the unsaturated zone is calculated using the Van Genuchten method.

Vertical cut off walls are presented in the model as soil layers in the filtration area with specified parameters (Table 1). In the chosen cross-section of the levee, on the boundary between the levee and the river a Dirichlet boundary condition is given with a total value of H, which corresponds to the water level in the stream. Exit face boundary conditions are used on the downstream slope and the downstream surface area.

4. Results

The filtration calculations were performed for two cut off wall location variations and for the actual situation (KP model), which reflects the current state of the levee. In the first model (P) both cut off walls are located in the centre of the levee's body (Fig. 2).

In the second case (GP), the cut off walls are located in the upstream slope near the toe of the levee and interact with an impermeable membrane (Fig. 3). The minimum distance between the geomembrane and the upstream slope surface should be 1 meter and the inclination of the upstream slope should be milder than the one of the geomembrane. In both cases, the cut off walls reach a depth of 9 m below the surface.

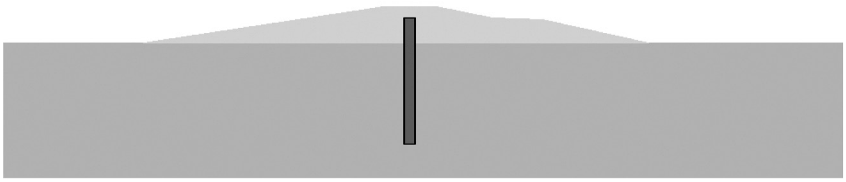

Fig. 2. ‘P’ model representing the levee with a cut off wall located in the centre

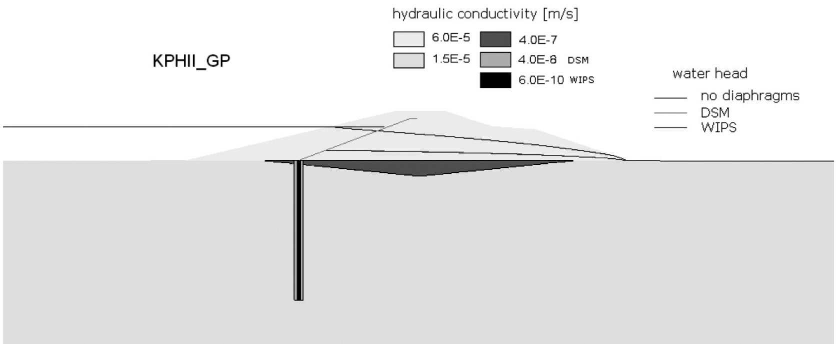

Fig. 3. ‘GP’ model representing the levee with a cut off wall located in the upstream slope and interacting with an impermeable membrane

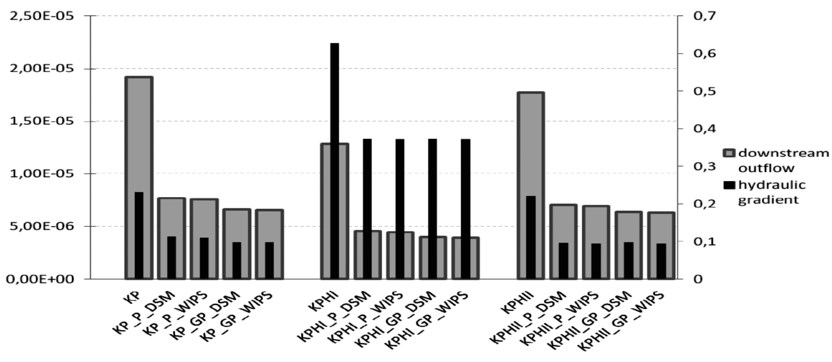

Fig. 4. Water head position with and without diaphragms on the upstream side interacting with a membrane (GP) for a homogeneus foundation model with a layer of silty sediments 20 m wide (KPHII)

The position of the water head in the body of the levee was calculated for all possible combinations of foundation, cut off wall position and technology (18 in total). As a result, it was shown that for a steady state water flow, the water head position is independent of the technology that the cut off wall was constructed in. For all foundation models, the groundwater head in the levee was almost the same for cut off walls made with WIPS and DSM technology. As an example, Fig. 4 shows the calculation results for the KPHII foundation model with the diaphragm interacting with a membrane. It is also clear that the diaphragm located in the upstream area and interacting with a membrane lowers the groundwater head sooner, influencing a decrease in the total water content in the levee's body.

For effective assessment of the cut off walls, an analysis of other parameters was taken into account, namely, the hydraulic gradient in the downstream toe area and the intensity of the water outflow downstream. Fig. 5 confirms that for all foundation models, locating the cut off wall on the upstream side interacting with a geomembrane give slightly better results in terms of limiting filtration. Table 2 presents the percentage values of these parameters, where 100% correspond to the initial situation without any diaphragms in the levee.

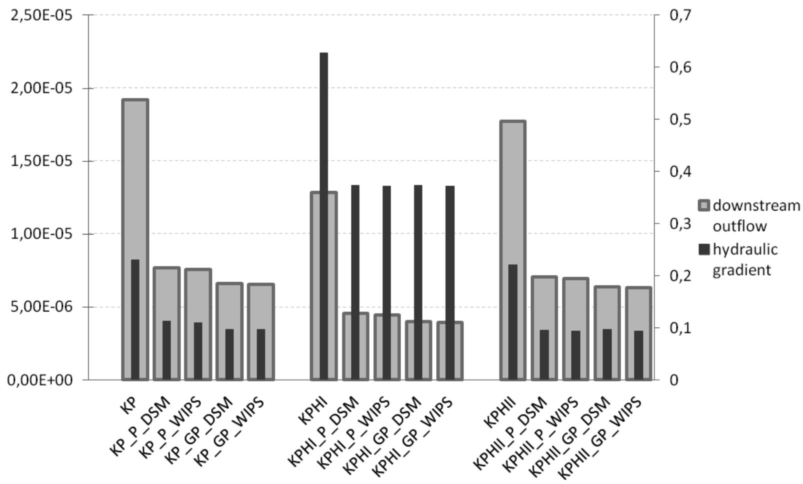

Fig. 5. Downstream outflow and hydraulic gradient change analysis after construction of DSM and WIPS cut off walls

Table 2

Effectiveness of cut off walls for different locations, foundation models and technologies

Numerical model	Downstream outflow reduction effectiveness		Hydraulic gradient reduction effectiveness	
	DSM	WIPS	DSM	WIPS
KP_P	48%	48%	40%	39%
KP_GP	42%	42%	34%	34%
KPHI_P	60%	59%	36%	35%
KPHI_GP	60%	59%	31%	31%
KPHII_P	43%	43%	40%	39%
KPHII_GP	43%	44%	36%	36%

5. Conclusions

The calculations of steady state seepage for the selected section of a levee on the Warta River in the area Kostrzyń allow for the drawing of the following conclusions:

– Cut off walls constructed in the WIPS or DSM technology can be successfully included in a numerical model of filtration through a levee as areas of a particular geometry and a known hydraulic conductivity.
– None of the diaphragms regardless of technology used and the location does not eliminate the free water outflow on the downstream side of the levee, however they all prevent the water from flowing through the downstream slope.
– Cut off walls made in the same location using different technologies give very similar results in terms of the position of the groundwater table and reducing the hydraulic gradient and the outflow on the downstream side.
– The cut off walls located near the upstream slope and interacting with an impermeable geomembrane proved to be more effective than the ones located in the centre of the levee.
– Each case related to flood security and solutions offered must be considered individually, so that the effectiveness of the proposed protection system is optimized for the given conditions.
– Simulations should be performed for several variations of the proposed flood protection to assess their effectiveness and select the optimal technical solution to eliminate irregularities in the course of filtration.

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