

SPATIAL, NUMERICAL MODEL OF FILTRATION FOR ŻELAZNY MOST TAILINGS MANAGEMENT FACILITY

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Abstract: The paper presents the results of calculation of 3D model of water filtration within the area of the Żelazny Most facility. Construction of numerical model of flow using finite elements method was preceded by gathering all available geological and hydrogeological data concerning the base, on which the facility is placed. Geotechnical investigations of the tailings management facility showed the substantial variability of filtration ratio inside the impoundment, what required to separate, from the whole area, the sub-areas with different hydrogeological properties. Three-dimensional filtration model was calibrated in the respect of filtration ratio and infiltration volume from the facility level into the free water table.

Streszczenie: Przedstawiono wyniki obliczeń trójwymiarowego modelu filtracji wody w obszarze zbiornika osadów Żelazny Most. Budowa numerycznego modelu przepływu z wykorzystaniem metody elementów skończonych była poprzedzona zebraniem dostępnych danych geologicznych i hydrogeologicznych podłoża, na którym posadowiono budowlę hydrotechniczną. Badania geotechniczne składowiska wykazały, że współczynnik filtracji zmienia się w istotny sposób w samym składowisku, co wymagało wydzielenia z całego obszaru podobszarów o różnych właściwościach hydrogeologicznych. Trójwymiarowy model filtracji poddano kalibracji ze względu na współczynnik filtracji i wielkość infiltracji z poziomu składowiska do zwierciadła swobodnego.

Резюме: Представлены результаты расчетов трехразмерной модели фильтрации воды в области осадочного бассейна Желязны Мост. Построение численной модели течения с использованием метода конечных элементов было опережено собранием доступных геологических и гидрогеологических данных основания, на котором была заложена гидротехническая постройка. Геотехнические исследования складской площадки обнаружили, что коэффициент фильтрации изменяется существенным образом в самой складской площадке, что требовало выделения из всей области подобластей, характеризующихся разными гидрогеологическими свойствами. Трехразмерная модель фильтрации была подвержена калибрации из-за коэффициента фильтрации и величины инфильтрации от уровня складской площадки по свободное зеркало

1. INTRODUCTION

Process of underground water filtration modeling within the area of Żelazny Most and on its natural vicinity is very difficult due to complicated hydrogeological condi-

tions both in the base on which the facility is placed and also due to highly non-linear variability of the filtration ratio ([2] and [5]) as well as filtration anisotropy on the impoundment area. Filtration flow calculations were made using numerical finite elements method contained in FlexPDE v.6 software [6]. Calculations were made for several variants of boundary conditions in order to find the best possible matching the free water level with the water level determined basing and piezometric measurements and verification of calculated wells, drainage and band ditch discharge. Construction of numerical model of underground water flow within the area of impoundment and its vicinity is of great importance for evaluation of tailings deposition safety from the perspective of KGHM Polska Miedź SA copper mines. Transfer of numerical calculations into GIS tools allows for full comparison of the free water level shape with the shape generated using piezometric measurement results.

The three dimensional shape of free water level was determined through calibration of model, consisting in selection of appropriate values of water filtration and infiltration ratio. To achieve this goal it was necessary to use great number of measuring data gathered and organized in the study of research team of KGHM CUPRUM – CBR [2] as well as results of laboratory tests presented in [1]. Despite the monitoring of the facility, there is no information about the contact of free underground water level with the water pond. Thus it was necessary to make calculation in few versions, through determination of boundary conditions of the problem, including computations taking into consideration:

a) assumptions concerning contact of with water pond:

- when free water level contacts with water pond,
- when free water level does not have contact with water pond,
- when water table has partial contact with water pond,

b) assumptions concerning operation of drainage systems:

- case, when all drainage systems (wells, band ditch, drainage under the basic dam, both ring drainages) operate,
- case, when the first level of ring drainage does not operate as a first level of drainage and other systems operates as described above,
- case when first level of ring drainage operates, but second level ring drainage does not yet operates, while other drainages operates as in first case,
- case when two ring drainages do not operate (water table is below those drainages), while other drainages operates as in first case.

2. MATHEMATICAL MODEL OF FILTRATION FLOW

In order to construct the numerical the hydrodynamic model of hydraulic filtration flow model for unsteady flow was used in calculations. For this case, based on [4], the filtration equation has the following form:

$$k_x \frac{\partial}{\partial x} \left(\frac{\partial(H - H_0)}{\partial x} \right) + k_y \frac{\partial}{\partial y} \left(\frac{\partial(H - H_0)}{\partial y} \right) + k_z \frac{\partial}{\partial z} \left(\frac{\partial(H - H_0)}{\partial z} \right) = \eta_e \frac{\partial(H - H_0)}{\partial t} \quad (1)$$

where:

H – means hydraulic head measured in relation of any basic level (in our case meters above sea level)

H_0 – means assumed ordinate of impermeable bed,

k_x, k_y, k – filtration ratio towards x, y and z axe,

η_e – is a coefficient of elastic capacity.

The above linear equation for the unsteady flow is an accepted mathematical model for calculating the hydraulic head on the area of impoundment and its vicinity. Model takes into consideration changes of filtration ratio on the Želazny Most area.

During the preliminary stage of calculations, in order to determine the initial free area of filtration flow, the model of Boussinesq [3] was used. The model is expressed by the following nonlinear equation:

$$k_x \frac{\partial}{\partial x} \left((H - H_0) \frac{\partial(H - H_0)}{\partial x} \right) + k_y \frac{\partial}{\partial y} \left((H - H_0) \frac{\partial(H - H_0)}{\partial y} \right) + \varepsilon = \mu_e \frac{\partial(H - H_0)}{\partial t}, \quad (2)$$

where:

ε – infiltration intensity, μ_e – effective soil porosity.

3. PHYSICAL PARAMETERS AND BOUNDARY CONDITIONS OF MODEL

Geometric data for calculations were taken from survey, piezometric, well and drainage measurements for the period 01.07.2007–30.06.2008.

While building the numerical model, the area of interest was divided into regions with different physical parameters of porous medium, including filtration ratio.

Filtration properties of sediments are the consequence of the impoundment construction technology i.e. deposition “toward center”. Discharge of tailing is made from the dam onto the beach. Mixture of tailings and water sediments while flowing towards the lowest point of impoundment. Bigger grains settle close the dam, while the smaller ones in the middle of facility. Distribution of filtration ratio on the impoundment area is presented in [2]. Using the above data, the initial average values of filtration ratio were taken in leaps for all 9 regions. In the process of model calibration the output values where changed is such manner to have yield values results obtained in calculations of horizontal and vertical drainage we close to the measured ones.

The first stage of calculation for each version of free water level was made basing on Boussinesq theory, assuming such values of filtration intensity coefficients for each region to obtain the shape of water table the closest possible to the surface obtained from the piezometric measurements. The second important factor during the model cali-

bration was value of vertical and horizontal drainages output from numerical calculations compared to those values obtained from the direct measurements. The obtained values of filtration are simultaneously calculative factor of the impoundment leakproofness in the vertical direction. Boundary conditions of the problem differ in three investigated versions of solution. Their detailed description is presented in [3].

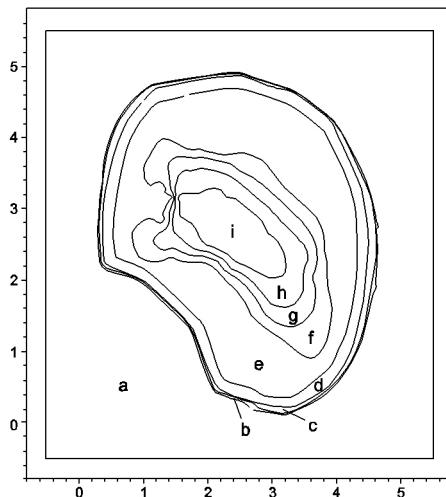


Fig. 1. Spacing of regions – birds view:
 a – region 1; b – region 2; c – region 3; d – region 4; e – region 5; f – region 6;
 g – region 7, h – region 8, i – region 9

4. RESULTS OF 3D MODEL CALCULATION FOR SELECTED VARIANTS OF COMPUTATION

Three-dimensional model of filtration flow was made using Flex PDE v.6 software. The calculations were made for several versions of boundary conditions as in case of 2D calculation of filtration based on Boussinesq [3] model.

Calculations for 12 versions of boundary conditions (see table 1) were made repeatedly, in order to obtain the result as close as possible to the measured values. Two very important criteria were assumed during the model calibration:

- adjusting the underground water level shape calculated from the model to the shape of water table from the measurements in piezometers,
- comparing calculated outputs of wells and horizontal drainage system with regard of measured outputs.

Concerning the first criterion, beside the visual evaluation of differences between water table shapes, measured and calculated, the numerical parameter, evaluation in macro scale the relation between both surfaces, was determined.

In order to describe in numerical manner, the degree of fitting the calculation results concerning the free water level from mathematic model to the reference surface from measurements, it was introduced the parameter describing the relative integral factor ξ of the obtained solution:

$$\xi = \frac{V_{\text{pom}} - V_{\text{obl}}}{V_{\text{pom}}}, \quad (3)$$

where:

V_{pom} – describes the volume of area between free water table according to measurements in piezometers, and the reference surface (surface on the ordinate 90 m b.s.l.) within the concerned 6×6 km field,

V_{obl} – describes similarly the volume of area between free water table according to calculations, in piezometers, and the reference surface (surface on the ordinate 90 m b.s.l.) within the concerned 6×6 km field.

The described factor is one of many possible ones describing the degree of fitness of both surfaces. It shows if, in the subsequent attempts of model calibration, we approach or recede from almost perfect closeness of both planes. Table 1 presents final values of the factor for each computation variant after several steps of model calibration.

Table 1
Comparison of ξ index after model calibration

Type of calibration	V_{pom}	V_{obl}	dV	ξ
No contact with water pond				
1. All drainages	0.4367	0.5384	0.1017	23.2883
2. Without I ring level	0.4367	0.5266	0.0899	20.5862
3. Without II ring level	0.4367	0.5294	0.0927	21.2274
4. Without ring drainages	0.4367	0.4305	-0.0062	-1.4197
Full contact with water pond				
1. All drainages	0.4936	0.5692	0.0756	15.3160
2. Without I ring level	0.4936	0.5576	0.0640	12.9660
3. Without II ring level	0.4936	0.5723	0.0787	15.9441
4. Without ring drainages	0.4936	0.5307	0.0371	7.5162
Partial contact with water pond				
1. All drainages	0.4947	0.5498	0.0551	11.1381
2. Without I ring level	0.4947	0.5384	0.0437	8.8336
3. Without II ring level	0.4947	0.5433	0.0486	9.8241
4. Without ring drainages	0.4947	0.4456	-0.0491	-9.9252

Value of V_{pom} is different for tree assumed shapes of water table i.e. the full contact, partial contact or absence of contact with of free water table with water pond. In each case the numerical model of free water table was generated in different way.

The best accordance of free water table shape obtained from measurements in piezometers and calculations was for the case when absence of contact between free water level with water pond is assumed and ring drainages are not taken into consideration.

The second important criterion was comparing the values of obtained outputs for vertical and horizontal drainage in each variant of model.

After analyzing the results of model calibration, it was acknowledged the closest to the measured values are two cases:

1) the one for the absence of contact between the free water table and water pond and when both levels of ring drainage are ignored,

2) the one when we have partial contact of free water table with water pond and water table has contact with ring drainage of I-st level.

Below we present the calculation results only for the case with absence of contact with free water table and water pond and when both drainage levels were ignored.

This case referred to the following boundary conditions:

- Water table has not the contact with water pond.
- On the area of impoundment the water filtration through the aeration zone is taken into consideration, and its intensity was determined during the model calibration.
- The case takes into consideration operation of all types of vertical drainage, except ring drainages, and into the place of drainages operation Dirichlet type condition (value of water table ordinate for the certain moment of time) was introduced.

It was assumed that the water level in case of horizontal drainages determine the ordinates of drainage location and predicted water level in the drainage or in dewatering ditch. The possible deviations from assumed values of ordinates for individual drainages resulting from displacement processes within the impoundment, were not taken into consideration.

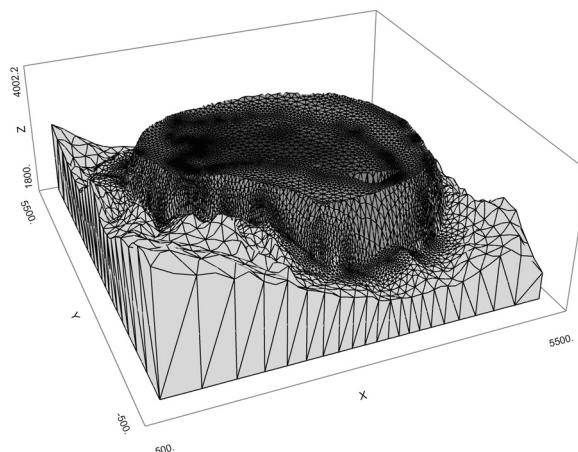


Fig. 2. Net of finite elements for 3D model

Three-dimensional net of finite elements in the „contaminated” scale, where overmatch is twenty-fold of x, y dimension, was presented on figure 2.

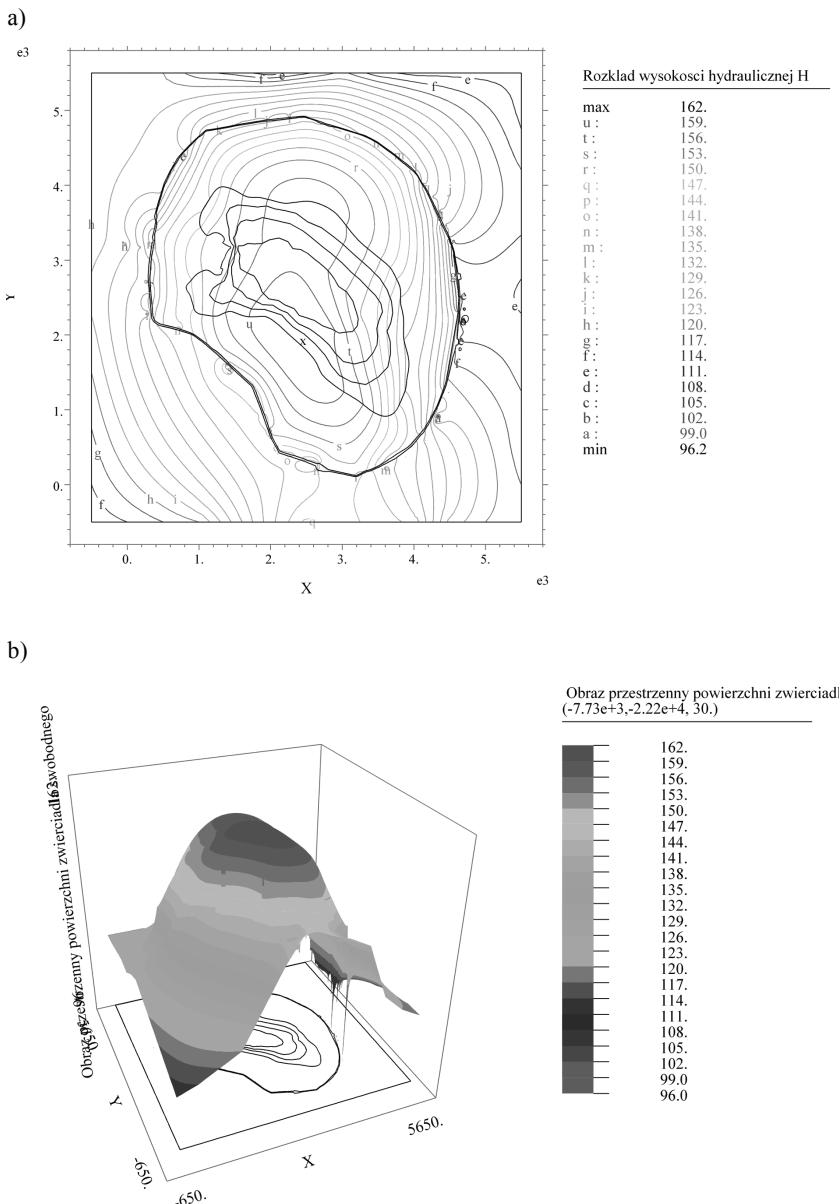


Fig. 3. Isolines of free water table:
a) shape of isoline on xy plane, b) 3D picture of generated water table shape

As a first condition for initial shape of free water table for each considered calculation variant, the results of 2D model computer simulation, described in [3], were taken into consideration. For the individual above discussed boundary conditions, model was calibrated each time and the optimal shape of free water table was searched changing the intensity of filtration through the surface of free water table and value of k filtration coefficient. In that way, through interaction, the free water table shape close to the one got from the piezometric measurements was obtained. Isolines of water table position are showed on figure 3, in the manner taken from FLEX PDE6 software, on the background of the facility bowl.

In figure 3a it was assumed that the distance between water level surface isolines is 2 m. The software allows for export of H value to the text file in the form of grid, what in turn let to transfer the received surface of free water table into every GIS or CAD software. To present the results MicroStation was used while numerical model of free water table was generated using InRoads software made by Bentley. It was compared with numerical model of free water table generated using the measurement results for the particular moment of time (the same moment of time, who which calculations using Flex PDE v.6 software were made).

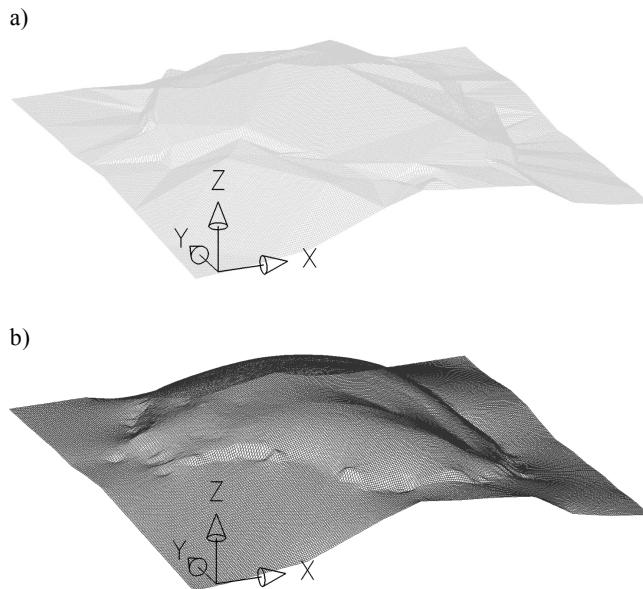


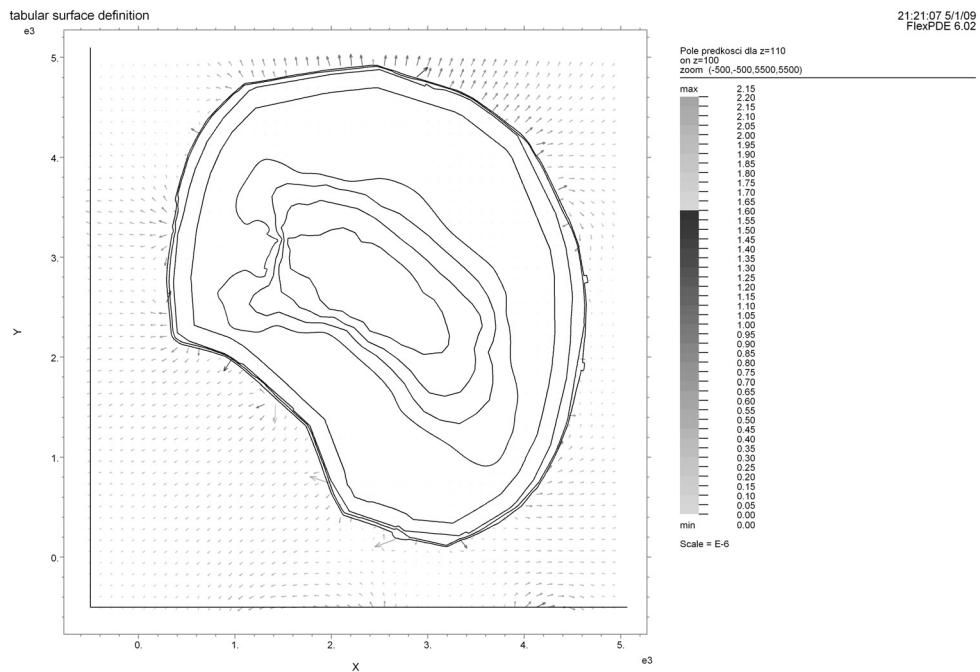
Fig. 4. a) water table generated in MicroStation using piezometer measurements,
b) water table generated in MicroStation using numerical model of filtration

The results of calculations for individual drainage systems show that calibration gives good concordance of the measured and calculated values. Important element of compliance analyze in comparison of water table shape from piezometric measure-

ments and from calculations. In figure 4 below, the position of both surfaces (calculated and measured) generated from the surface model of water table in tools of MicroStation and InRoads.

Calculations of tree dimensional model allow to analyze the filtration stability of the impoundment. Calculation results show that for the case studied in this report, there is not any loss of filtration stability inside the impoundment area.

In the figure 5, below, the velocity field of filtration expressed in components (v_x, v_y) on the plane having the ordinate of 112 m is presented.



Filtracja_ZM_3D_v8_30: Grid#1 P2 Nodes=348102 Cells=221963 RMS Err= 0.0114

Fig. 5. Velocity field of filtration

5. SUMMARY

The paper presents results of numerical calculations of the filtration flow for the tree -dimensional model within the area and in the vicinity of „Żelazny Most” tailings management facility. With regard of 3D model the problem comes down to solve the equation (2.1) for the filtration area with unknown boundary. This unknown boundary is the free water level. Comparing the calculation results concerning the free water level we can state that 2D model, in spite of applied simplification, allows to obtain

the shape of free water table with high accuracy and finally gives the results similar to 3D model.

The results of calculations for 3D model show that within the area of filtration does not occur the loss of filtration stability. Detailed analyzes indicate the sub-regions, on which the component vectors of v_z velocity have the opposite sense to the operation of gravitation field forces vector, but the value of local drops is smaller than the boundary value. The impoundment and its base consolidation were not taken into consideration, Thus in reality local gradients of hydraulic head, may occur, much higher than the ones calculated for the presented model.

The calculations made for twelve variants of multiple model calibrations show also that:

- the model assuming the disruption of surface water pond, having the free water table with absence of ring drainages, gives the best global approximation between the water table and assumed related surface, since the coefficient for this case is $\xi = 1.42$. Thus there are two zones of water flow i.e. filtration zone and infiltration zone,

- measured water outputs for ring drainages are small and confirm the conclusion resulting from the analyze of the individual computation variants, that at this stage of impoundment construction those drainages do not operate as one of the elements of drainage system. After raising the impoundment crest it is very likely that they will play an important role in shaping the free water table,

- calculations, taking into consideration the infiltration zone, and assuming that the water table is close to the water pond (obtained using DTM), enable to determine anisotropy coefficients of impoundment body through the model calibration,

- the anisotropy coefficients determining the quotient of filtration ratio in vertical direction versus filtration ratio in horizontal direction, change vitally with the approaching to the area located in the lowest part of water pond.

All numerical calculations, i.e. concerning the mathematical model, the approximation (model DTM) and interpolation (model GRID) permit to state that the proposed calculation method using the finite elements procedure, leads to good approximation of reality and is the right step towards construction of tree dimensional model of the filtration flow within the impoundment area and its surroundings with full consideration of native soil geology. Such model may be an important element of monitoring the filtration within the impoundment area and also a vital element during describing the stress and deformation state inside the facility, rheological processes within its area and its stability.

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