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NUMERICAL DIMENSIONING OF VERTICAL GROUT CURTAINS OF EARTH-FILL DAMS

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Abstract: This study presents theoretical principles and practical approach to the computations carried out for a grout curtain of an earth-fill dam. The computations were performed within a particular case study of the structure for which the indispensable initial data had been collected both with respect to the structure itself, as well as to the subsoil – previously subject to thorough investigation. The data included geo-engineering and hydro-geological documentation which entailed the area in front of and behind the dam structure, but also the areas where alarming phenomena occurred, associated with the filtration of water under the dam.

Using a numerical tool, i.e. the FlexPDE program, the calculations were made for the purpose of determining the reasons for the ensuing faulty situation and in order to assess the possible consequences if the risky situation prolongs. With the intention of meeting potential threats, the installation of a grout curtain was suggested, not only in the threatened area, but also over the entire length of the structure under survey. The computations made it possible to confirm the rightness of the choice of the above-mentioned solution, to determine the required depth of curtain's position and to suggest the technology of its making.

1. ASSUMPTIONS OF MODELING GROUNDWATER FLOW

In order to describe the process of water flow in the ground, three fundamental equations have to be used, complemented with the boundary and the initial conditions of the issue under survey [5], including:

- **Constitutive equation of state** (1), which describes elastic deformation of both the soil skeleton and of the fluid under the influence of the changing pressure in the fluid (Hooke's law).
- **Equation of flow continuity** (2)**,** which describes the total gain in the mass of the fluid flowing in the VER area, in time and in particular directions, in comparison with the balance of the fluid that flows in and that flows out of a given area (mass conservation law).
- **Equation of motion of the fluid** through a porous medium (3), which describes the motion of a viscous Newtonian fluid through the pores of a solid body (Newton's Second Law).

The issue under investigation is the model of the flow of an incompressible fluid through a non-deformable porous medium; hence, the above mentioned equations are as follows:

$$\rho = \text{const}\,, \tag{1}$$

$$\text{div}\vec{v} = 0\,, \tag{2}$$

$$\vec{\upsilon} = -\,k\,\overrightarrow{\text{grad}}\,(H) = \overrightarrow{\text{grad}}\,\Phi\,. \tag{3}$$

2. POSSIBILITIES OF NUMERICAL MODELING

Due to the global type of the issue in question, i.e. the filtration of water within the earth-fill dam that encloses a storage reservoir, the tool selected for its survey was the FlexPDE program [8]. In this program, the soil environment in which the motion of water takes place is described by means of the finite element method; the program is, therefore, an appropriate instrument for solving the problems referring to large-size structures.

Using the FlexPDE program, we have to obtain the boundary as well as the initial values of the design problem in two or three spatial dimensions. Differential equations, used in order to describe the phenomenon, are of the first or the second order, oriented both in time and space. If it is necessary to apply the equations of a higher order, they have to be written as a system of equations of a lower order. The functions, in turn, may be formulated with the help of linear or non-linear equations, and the FlexPDE program adjusts the solution path automatically. The number of equations to be solved by the program at a time is limited, but only by the parameters of the program user.

The solution obtained in the form of boundary and initial values is presented by the program by means of a contour and it entails the lot, the lot's surface area, elevation angle, area vector, etc.

3. THE REASONS BEHIND SELECTION OF STRUCTURE UNDER SURVEY

There were the following reasons behind the selection of the structure to be analyzed in detail in this study [3]:

– the solutions chosen by the designers of the structure, after they had detected that the subsoil in the structure's area has natural leak-tight properties,

– very interesting arrangement of the subsoil layers under the reservoir bowl, as far as filtration phenomena are concerned: permeable layers alternate with poorly permeable layers,

– the fact that two years after the structure came into use, there already showed the seepage of water on the dam's downstream slope,

– the observation that in the conditions of normal water impoundment in the dam, the level of water in the drainage ditches (which carry away the water from the drainage of the toe of the dam) increased by about 0.10 m,

– the fact that the dam came into use not long ago, and the solving of the current problem may prevent potential failure of the structure.

4. STRUCTURE OVERVIEW

The Przeworno Storage Reservoir is a typical example of a small retention structure [4]. It came into use in 2007. The basic parameters of the reservoir are as follows:

- Total capacity – 0.851mln m^3,
- Active capacity – 0.315 mln m^3,
- Surface area within the boundaries of the regular reservoir – 37.4 ha,
- Reservoir surface area at full pool – 81.0 ha.

The reservoir is located at a distance of about 600 m to the east of the village of Przeworno, in the valley of The Krynki River, which is a right-bank tributary of The Oława River.

The earth-fill dam was situated at the 16+350 km of the course of the river. The reservoir bowl is gently bordered from two sides by the slopes of the hills surrounding the river valley.

The earth-fill dam that encloses the reservoir has been categorized as belonging to the 3rd class of hydrotechnic building importance [2] and was made of sandy soils: sand-gravel mix and medium sands. The dam is 510 m long and its maximum height equals 5.30 m. The normal level of water storage was assumed at the datum of 185.0 m AMSL (above the mean sea level), and the maximum level – at 186.0 m AMSL; the crest of the dam – at the datum of 187.0 m AMSL, and the inclination of the upstream and the downstream slopes was designed as 1:3.

Fig. 1. General view of the reservoir

Fig. 2. The view of the dam's upstream slope

Fig. 3. The view of the dam's frontal overflow crest in normal conditions of water storage

5. NUMERICAL COMPUTATIONS

In accordance with the information obtained [1], the observed seepage is located near the borehole no. 6 (figure 4); therefore, the following items were subject to analysis:

- geological section no. III–III (across the dam, figure 5), on the line of which the pursued point is located,
- geological section no. I–I (along the dam's axis, figure 6)
- by way of a check, geological section no. IV–IV (figure 7) was additionally surveyed, from the point of view of the filtration phenomena safety.

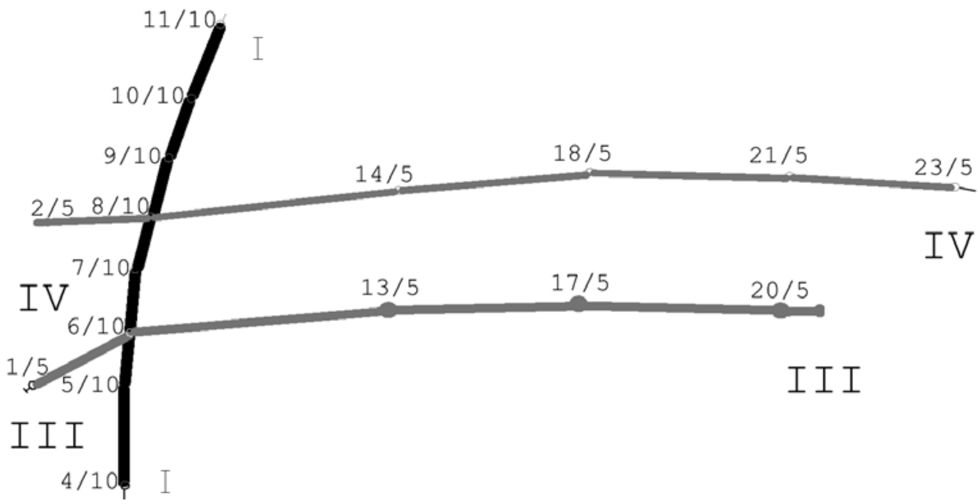

Fig. 4. The location plan of geological boreholes

For the purpose of numerical computations, the following preliminary computational assumptions were made [1]:

– due to the available initial data referring to the subsoil, it was decided that some simplifications would be introduced, which would make it possible to perform the analysis of the actual state, however, bearing in mind that the obtained solution will be as approximate to the actual course of the phenomena under survey as possible,

– due to a large number of interbeddings in the subsoil under the dam and the reservoir bowl, and because of a large diversity of subsoil types, a fundamental subdivision into three groups of soil was made: sandy soil, for which the permeability tensor was assumed at one level of $k_f = 2.60 \times 10^{-6}$ m/s, medium permeable soil, which includes silty and clayey soils with the permeability tensor at the level of $k_f = 21.0 \times 10^{-6}$ m/s, well-permeable soils that entail coarse sands, gravels and sand-gravel mix, for which one permeability tensor level was established with the value of $k_f = 1.0 \times 10^{-4}$ m/s. In addition, a fourth soil group was distinguished which includes the soil constituting the drainage system under the dam's body. Since the drainage system consists of gravel with no admixtures, its permeability coefficient, in accordance with the design guidelines, equals $k_f = 1.0 \times 10^{-3}$ m/s [6].

The assumptions and boundary conditions presented in the preceding chapter were introduced to the FlexPDE computer program. The data included:

– the Dirichlet boundary conditions, which determine the value of a given dependent variable as a function of fixed space coordinates and the values or derivatives of dependent variables, which depict, in the case under study, permeable boundary and free water table;

– the Neuman boundary conditions, which influence the way of writing the equations, but also refer to the specification on the region's boundary; those conditions are given in the form of the functions of fixed space coordinates and the values or derivatives of dependent variables – in this case describing the impermeable boundary and the contact surface of two areas with diverse permeability;

– mixed boundary conditions, which show the values of points on one boundary for replication or another, with the negation of boundary values which were determined by any coordinator of statement transformation. Mixed boundary conditions are appropriate when we consider such structures as sheet pile walls or drainage, when the strength of source depends on the position of the water table.

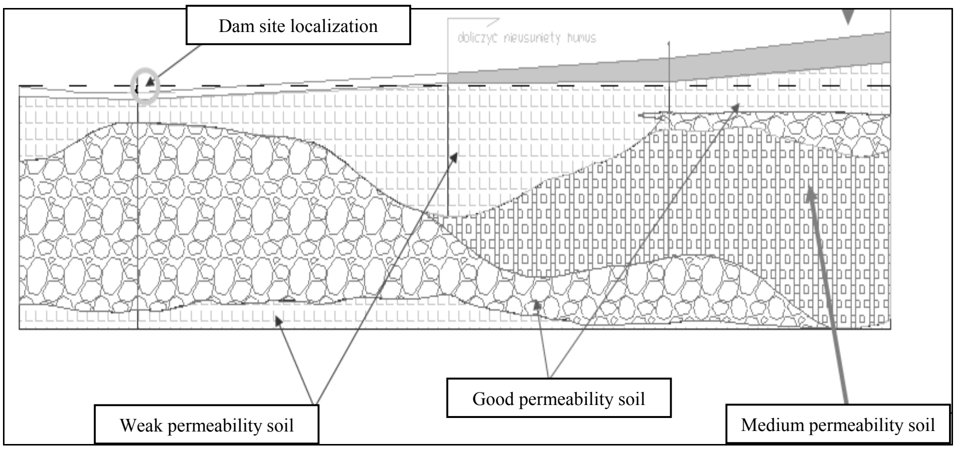

Fig. 5. Geotechnical section no. III–III, along the reservoir area

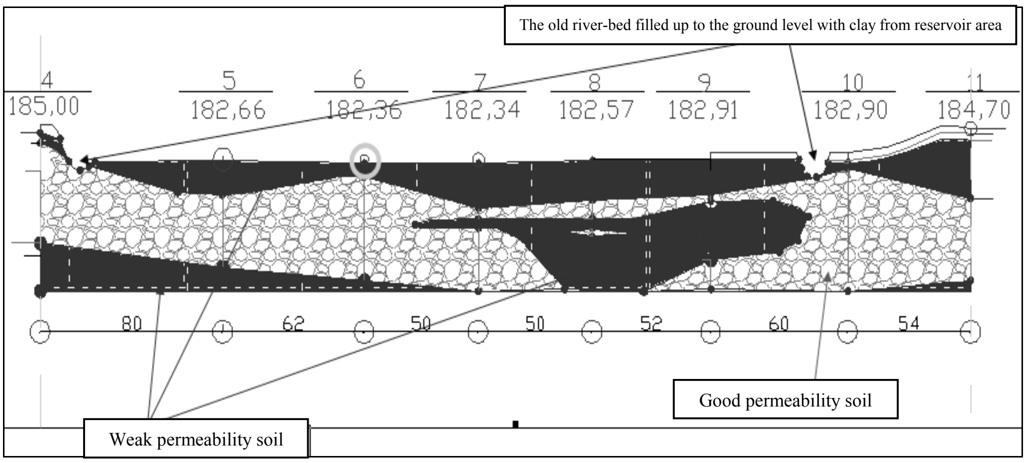

Fig. 6. Geotechnical cross-section no. I–I, along the dam's axis

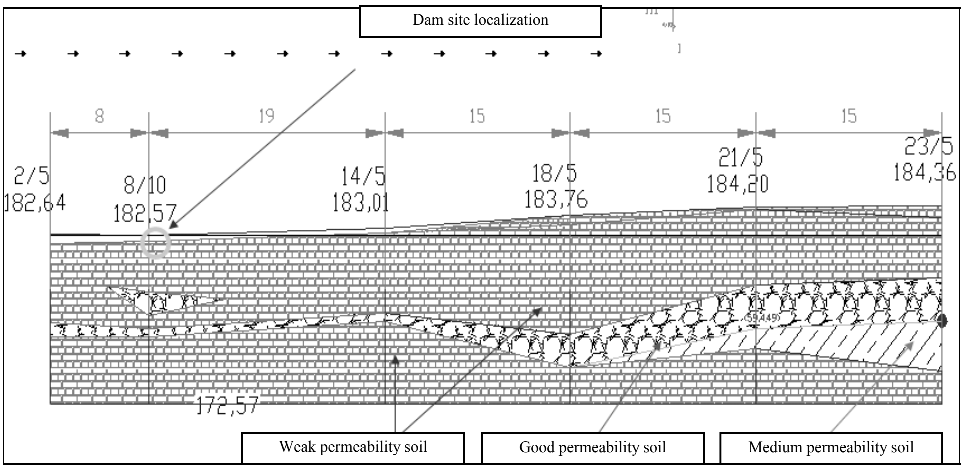

Fig. 7. Geotechnical section no. IV–VI, lengthwise across the reservoir bowl

Figure 8 shows a diagram presenting the above-mentioned boundary and initial conditions, required to be introduced to the computational program employed.

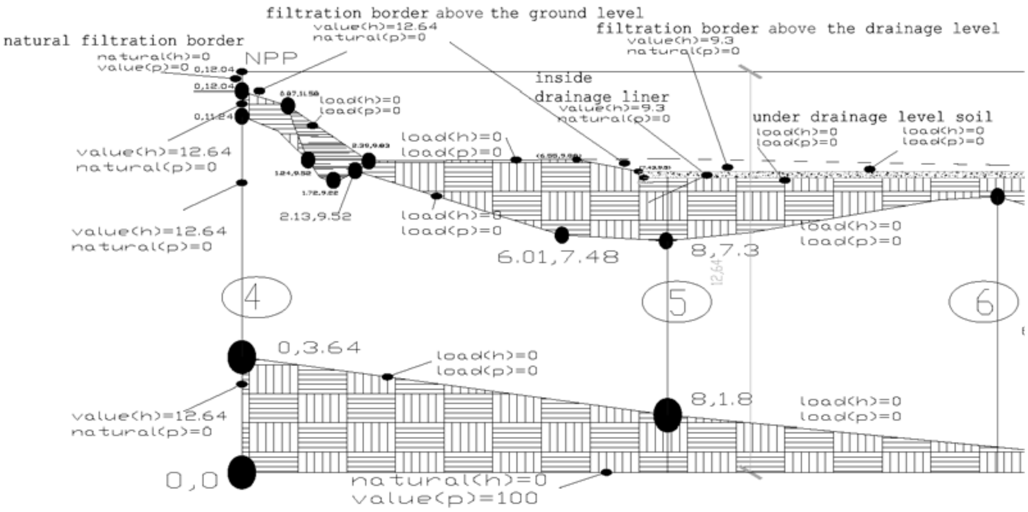

Fig. 8. Diagram illustrating assumptions and boundary conditions

6. COMPUTATION RESULTS AND THEIR INTERPRETATION

The computation results obtained are presented in table 1, for the selected section no. III–III which was considered most endangered [1]. Figures 9–13 consist of the print-outs from the FlexPDE program.

Table 1

Computation results of gradients within the sections under survey

Value	Section I–I	Section III–III	Section IV–IV	Extremum	Faulty section
i_{cr}	–3.6	0.0 ÷ –2.5	0.8	–3.6	Borehole no. 6
Filtration stability $i_{cr} > 0$	unstable	unstable	stable		Unstable no. 6 in sections III–III, I–I
Assessment/ Comments	unstable	dangerous	safe		

The results of the numerical computations performed show that the dangerous areas, as far as filtration is concerned, are both section III–III and section I–I, where the borehole no. 6 was made. The solution obtained confirms and justifies the fact that the operation and maintenance problems occurred just at that place. The section along the axis of the dam revealed explicitly a large uncontrolled seepage of water from the reservoir.

Numerical computations pointed to a difference between the hydraulic gradients for the section connecting the upper and the lower station of the dam. Those are the typical symptoms of the risk of a seepage failure [7]. Owing to the fact that the object has been in use for 2 years only, it is indispensable to carry out immediate works which will protect the place where the seepage failure might potentially occur. However, this will not be possible unless the soil near the dam's body is again investigated.

In the case of section III–III, the critical gradient reached the value of zero. This section is, therefore, not safe with respect to filtration properties. When dealing with the soil with a large content of silty and clayey fractions, it has to be taken into account that ($i_{cr} = 0$) such soil type, in the situation described in this work, may undergo softening and thus cause the risk of creating a so-called filtration duct, filled with the soil of a fluid or semi-fluid structure.

As far as section I–I is concerned, the critical gradient assumed a negative value. This accounts for a probable soil fluxing. Further use of the structure, without necessary strengthening and support, may lead to a construction disaster [7].

On the basis of the analysis of the section along the reservoir's axis it was tentatively assessed that between the 100th and the 170th meter of the dam's length, measured from the left abutment, the rule of filtration stability has been considerably exceeded. Due to the nature of the problem, the installation of a grout curtain along the whole length of the dam was suggested, in the area of regular storage extent. In order to specify the appropriate length of the curtain, a file that takes into account the variable of the curtain's length was developed [1]. The applied method of estimating the vertical extent of the curtain requires the estimation of discharge in two independent cross-sections, in order to compare the values of filtration groundwater flow.

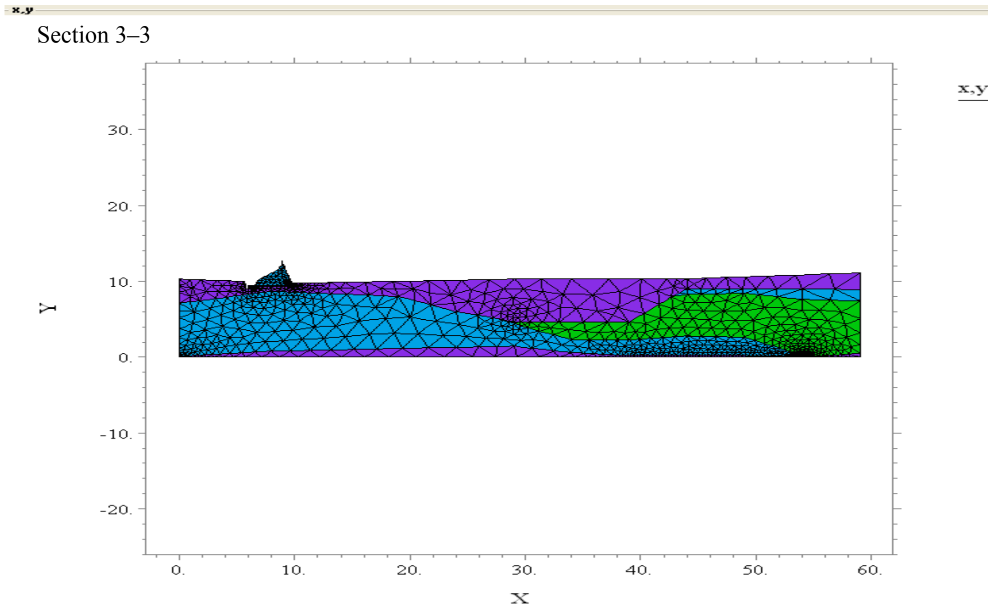

Fig. 9. Discretisation of the subsoil along section III–III (transverse to the dam's axis)

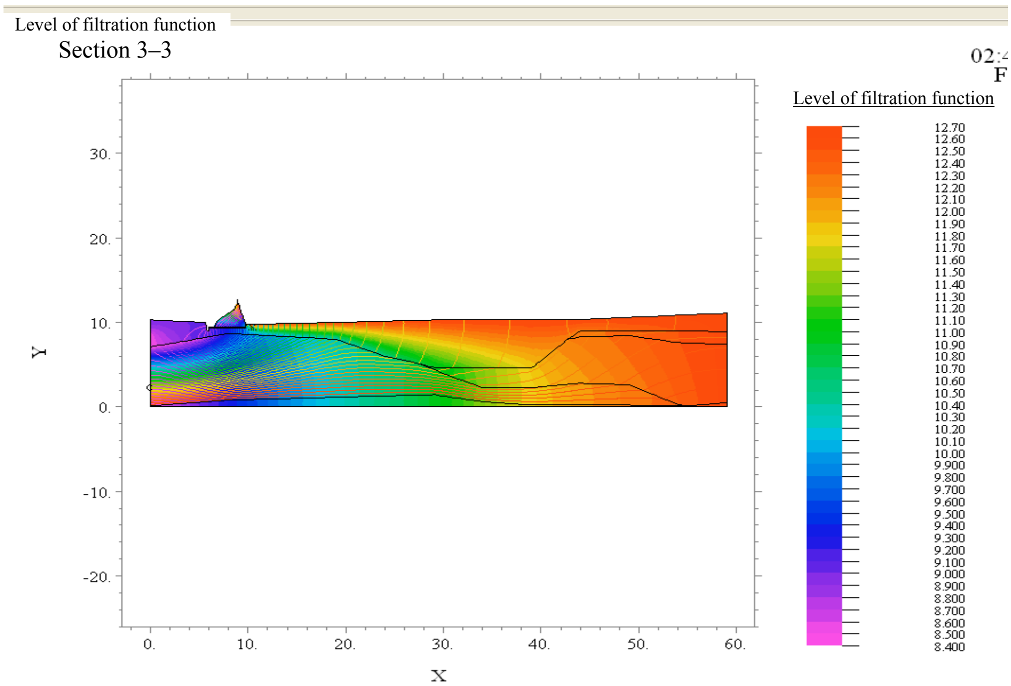

Fig 10. Subsoil characteristic with respect to filtration properties

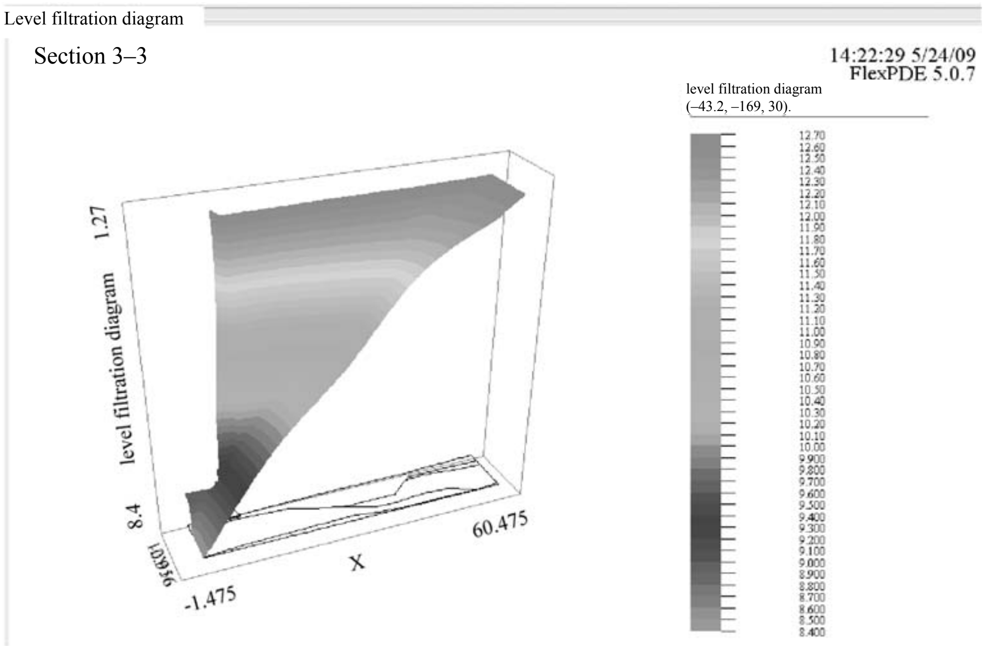

Fig. 11. Function of the potential, determined for a selected section

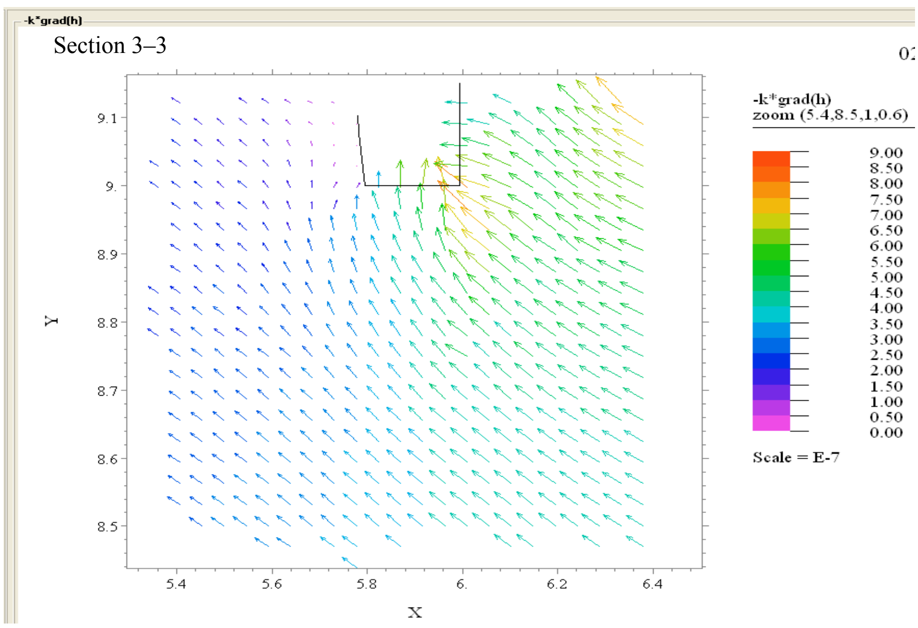

Fig. 12. Hydraulic gradients in the area under survey

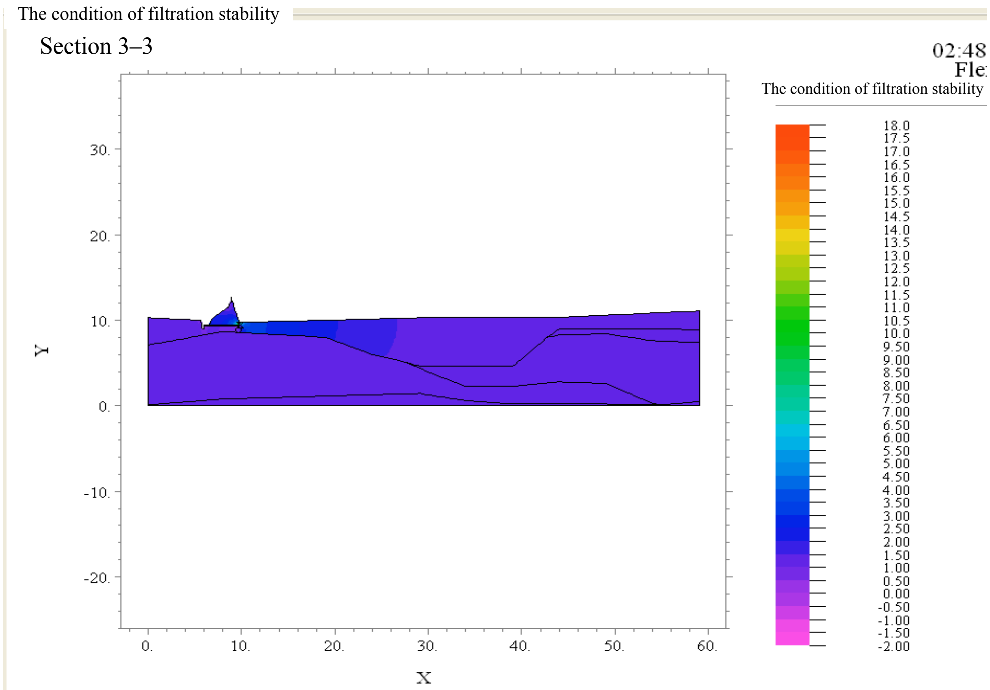

Fig. 13. The condition for filtration stability within the area under survey

As the numerical analyses have shown, the optimal solution is to use a vertical curtain down to the length of min. 6.60 m, that is, the level at which the stream function assumes the value of p = 84. In order to verify the estimation, a formula which takes into account the inserted barrier was developed, and the calculations were carried out once more [1].

From those calculations it appears that the insertion of the curtain increases the filtration safety factor from the value of 0.0 to 0.8, at the most critical place, i.e. on the foreground of the downstream slope of the dam.

7. SUGGESTED SOLUTION

Due to the character of the problem – uncontrolled water seepage from the reservoir – it was decided to use a vertical grout curtain made of the HDPE geomembrane (GEOLOCK). This is a screen that consists of single sheets of the HPDE geomembrane that are locked together. At present the reservoir's dam is sealed on the upstream slope by means of a bentonite hydroinsulating mat (bentomat), placed to a depth of about 12 m measured from the edge of the upstream slope; this sealing must be pierced and, subsequently, re-sealed using bentonite in the area of the piercing.

Bearing in mind the required depth at which the curtain should be submerged into the subsoil, a 3 mm thick sheet of the HPDE geomembrane was selected. Its joining with the adjacent sheets, the so called “lock”, will be made of 6 mm thick material, which ensures the stiffness not only of the geomembrane, but also of the lock itself. The geomembrane and the lock will be welded together. At the same time, in order to preserve the excavation stability, Geolock geomembrane will be introduced in the bentonite slurry.

For technological reasons, the length of a single strip of the system was assumed as equal to 6.60 m, and its width 2.20 m, which will be identical for the entire depth of the grout curtain. The barrier will be installed in the toe of the upstream slope (figure 14), at the section bordered by the axes of The Młynówka Canal riverbed and The Krynka River streamway. The overall barrier’s length will amount to 320 m.

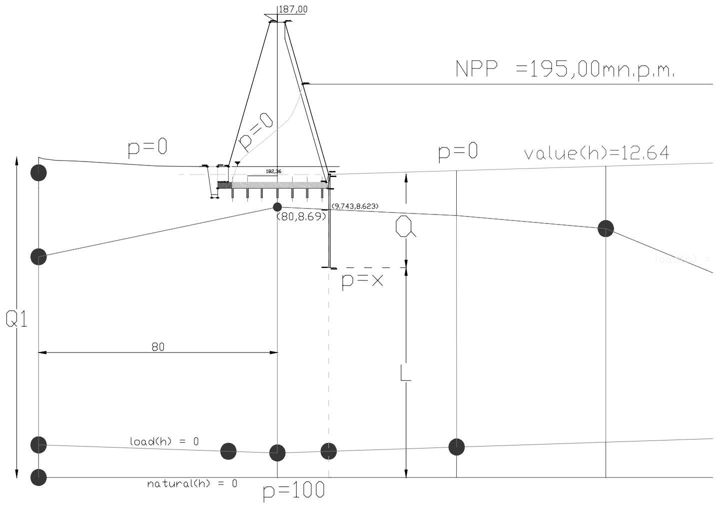

Fig. 14. Suggested location of the watertight barrier

8. SUMMARY AND CONCLUSIONS

This work presents the results of the analysis and assessment of the character and intensity of filtration phenomena within the subsoil on which the earth-fill dam of the Przeworno Storage Reservoir (on The Krynka River) was founded. On such basis, it was suggested to install a protection device in the shape of a grout curtain.

The example of the Przeworno reservoir confirms the validity of the often emphasized statement that it should never be assumed that the process of designing a given structure ends with the completion of the computations, and that each hydrotechnical structure should be thoroughly supervised – not only during the reservoir testing, but, above all, the monitoring should be continued in the course of the proper use of the facility.

In a situation where, after the structure had been put into use, there occurred a sudden and violent seepage in the subsoil, an immediate counteraction is indispensable. Neglecting the problem may lead, in consequence, to irreversible damage both in the subsoil, as well as in the structure itself.

The conclusions that may be drawn from the analysis of the available initial data and the numerical analyses carried out with the help of the FlexPDE program include:

1. It becomes indispensable to undertake a quick intervention in order to stop the filtration process detected in the field tests in the subsoil under the dam of the Przeworno Reservoir.

2. Since the cross-section in which the geological borings were performed does not overlap, as the design originally assumed, with the axis of the dam's body (it is shifted by about 40 m), it is necessary to investigate the subsoil again, this time in the appropriate and tested section; however, it is recommended that the section should be located precisely in the toe of the dam's upstream slope.

3. After the results of field tests are obtained, new design works must be carried out in order to verify the assumptions made beforehand, and to re-design the watertight barrier.

4. It is recommended to maintain a permanent control of filtration phenomena both in the body as well as in the foreground of the dam's upstream slope, by means of a system of piezometers arranged along the whole section of the dam. The arrangement of the piezoemeters in the dam's section should depend on the results of the repeated geotechnical survey.

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