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NUMERICAL THREE-DIMENSIONAL MODEL OF AIRPORT TERMINAL DRAINAGE SYSTEM

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Abstract: During the construction of an airport terminal it was found that as a result of the hydrostatic pressure of underground water the foundation plate of the building had dangerously shifted in the direction opposite to that of the gravitational forces. The only effective measure was to introduce a drainage system on the site. The complex geology of the area indicated that two independent drainage systems, i.e., a horizontal system in the Quaternary beds and a vertical system in the Tertiary water-bearing levels, were necessary. This paper presents numerical FEM calculations of the two drainage systems being part of the airport terminal drainage design. The computer simulation which was carried out took into consideration the actual effect of the drainage systems and their impact on the depression cone being formed in the two aquifers.

Key words: *numerical modeling, drainage system, depression cone*

1. INTRODUCTION

In 2011 during the construction of a new airport terminal, the foundation plate was found to have deformed vertically. It was hypothesized that the main cause of this situation was the clays occurring directly under the foundation plate, which had begun to swell in contact with underground water. It was determined, however, that the cause was the hydrostatic pressure of water under the plate, which was strong enough to locally exceed the stress produced by the building weight. The best way of immediately reducing the hydrostatic pressure turned out to be the use of piezometers drilled through the plate, releasing water in a controlled manner until the groundwater table stabilized at a level safe for the building. It was, however, only a temporary solution, not ensuring a permanent improvement. Therefore it was necessary to design a surface drainage system for the Quaternary deposits and a vertical drainage system for the deeper Tertiary parts in order to reduce the hydrostatic pressure in this area.

On the basis of data acquired from boreholes (Grzegorczyk et al. [1]) three structural stages were distinguished in the area investigated. The older crystalline base is built of Permian and Mesozoic rocks and it is covered by a complex of Cenozoic deposits. The Tertiary is represented mainly by variegated clays, silty clays and locally Miocene sands and silts. The exploration drilling results show that the top of the Tertiary (clays) occurs shallowly, i.e., from 0.5 to 4.8 m below the surface. Several meters thick layers and lens of fine and medium grained silty sands as well as silts and sandy silts occur at a depth of 4.0–11.0 m in the area of the airport terminal building. River sedimentation deposits, i.e., mixed sands, gravels and ice-dammed lake sedimentation clays, clayey sands and clayey muds occur on the Tertiary top. The total thickness of the deposits amounts to 0.5–4.8 m. From the surface downwards the area is covered by a soil and subsoil layer and locally by mineral and mineral-rubble material.

Two underground water levels were found to occur in the surveyed area. The first level (Quaternary), connected with the sandy deposits in the top of the impermeable clays, is generally characterized by a shallow water table occurring at a depth of 0.5–1.0 m below the surface. This water level has a variable depth depending on weather conditions and basement filtration. The water-bearing bed consists of fine-to-coarse sands and gravels. The groundwater level is assessed to be medium upper and periodically fluctuating by ca. 0.3–0.5 m. The permeability coefficients (k) determined on the basis of grain size distribution analyses and empirical tables for the particular types of permeable soils are as follows:

- fine sands $k = 1.7*10^{-5}$ m/s,
- medium and coarse grained sands $k = 9.3*10^{-5}$ m/s,
- gravels $k = 6.4*10^{-4}$ m/s.

The second (Tertiary) underground water horizon is connected with sandy inter beds enclosed within clays. The water belonging to this horizon was found in survey boreholes located south of the east side of the airport terminal building. The Tertiary water bearing horizon is built of silty to medium grained sands. The permeability coefficients k determined on the basis of grain size distribution analyses and empirical tables for the individual types of permeable soils are as follows:

- silty and fine sands $k = 1.04*10^{-5}$m/s,
- medium grained sands $k = 5.21*10^{-5}$ m/s.

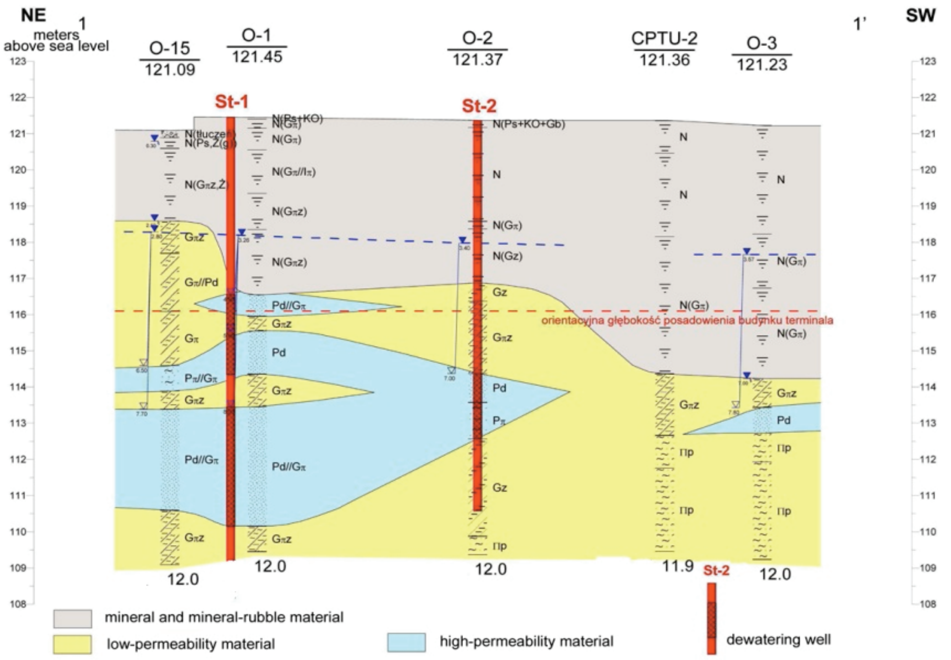


Fig. 1. Sample geological cross-section

A numerical model was built to determine the evolution of the three-dimensional shape of the groundwater table within the Quaternary bed, caused by the designed horizontal drainage and by the groundwater surface confined within the Tertiary deposits subjected to vertical drainage. The results were to be used to determine the depression cone extent in both the water horizons and to calculate the yield of the horizontal drains and wells for the purposes of a detailed vertical and horizontal drainage design. The calculations were performed using the finite element method and the Flex PDE v.6 software.

2. MATHEMATICALMODEL OF FILTRATION FLOW

The 3D hydraulic model of the filtration flow with the water table within the Quaternary formation, and of the flow under pressure in the Tertiary deposits was used for the calculations. It was assumed for the whole area that the Tertiary bed bottom is a plane surface located 105 m above the sea level. It was also assumed that the initial groundwater level is the same for both the aquifers and is consistent with the map of water table contours presented in the geological report [1].

The hydraulic model of the filtration flow, discussed in detail in study [3], was used for the calculations. Assuming that an unstable flow in an isotropic homogenous medium is considered, the differential equation has the form

$$\nabla^2 H = \frac{1}{a}\frac{\partial H}{\partial t}. \qquad (1)$$

Piezo-conductivity coefficient a is expressed by the following equation

$$a = \frac{k}{\eta_{spr}} = \frac{k}{\rho g(\beta_s + f\beta_w)} \qquad (2)$$

where β_s and β_w are respectively the volume compressibility of solid particles and that of water, ρ means the density of the water flowing through the medium, g – gravitational acceleration, k – a coefficient of permeability.

3. NUMERICAL MODEL OF AREA AND GEOLOGIC STRUCTURE

A 3D picture of the geological layers and a numerical model of the area with its surface infrastructure were generated for the needs of the underground water filtration model which takes into account the variable and complex geologic structure.

The maps were digitized using the Micro Station software [4]. The digitization covered the area surrounding the MLP passenger terminal and included contour lines, scarps, roads, height points and buildings within the borders of the area. Also the planned drainage systems were marked on the map. The individual data were placed on separate layers so that they could be input into the InRoads software.

Map digitization based on calibrated bitmaps was done in 3D and the obtained data were exported into the InRoads software [5] which generates a numerical model of the terrain surface and of the top and bottom of the aquifer.

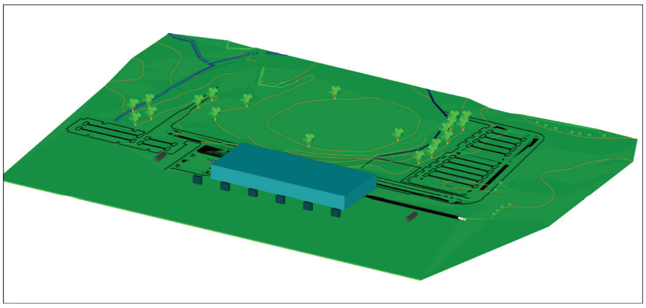


Fig. 2. Numerical model of the area surface

For the purposes of the design a 3D map of the area surface, with contour lines and height points placed on the proper level, was made on the basis of the raster of the primary map. The numerical model of the area surface is presented in Fig. 2. The surfaces for the individual rock types were generated separately and then exported into the Flex PDE v.6.33 software [6].

4. RESULTS OF NUMERICAL CALCULATIONS

In order to simplify the 3D filtration model the following assumptions were made:

- the Quaternary aquifer's thickness, coefficient of permeability and coefficient of piezo-conductivity are constant;
- the permeable Quaternary layer is in contact with the Tertiary layer in the north-west part (this assumption was not supported by any detailed geological survey);
- the calculations are to be made for the location of the horizontal and vertical drainage in accordance with the detailed drainage design;
- the calculations are for maximum 5 years;
- first only the impact of the horizontal drainage on the depression cone is to be calculated;
- after 2 years the vertical drainage begins to operate; the assumed average water table in the wells is to be determined for fluctuations amounting to 1.5 m.

The flow area was divided into 19 regions. The generated (by the FlexPDE v. 6.33 software [6]) finite element grid had 300798 nodes and 208914 tetrahedral finite elements and it is shown in the contaminated scale (variable z*20) in Fig. 3.

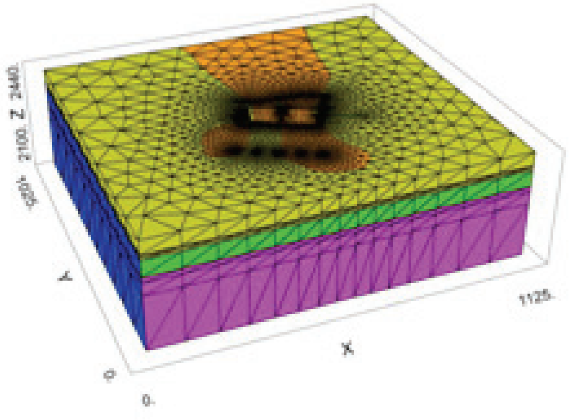


Fig. 3. Spatial grid of finite elements

The finite element grid for the area surface (vertical view) is shown in Fig. 4.

The surfaces of the contact between the individual rock layers are uneven. In the calculations, the layer system obtained from the geological surveys was simplified by assuming that the contact surfaces between the layers are planes and that the contacts between the layers change abruptly. It was necessary to adopt such a simplified geometrical model because of the lack of sufficient data for the area outside the airport terminal building since no detail geotechnical surveys had been carried out there. An exemplary shape of the layers on the 115.6 m level is shown in Fig. 5.

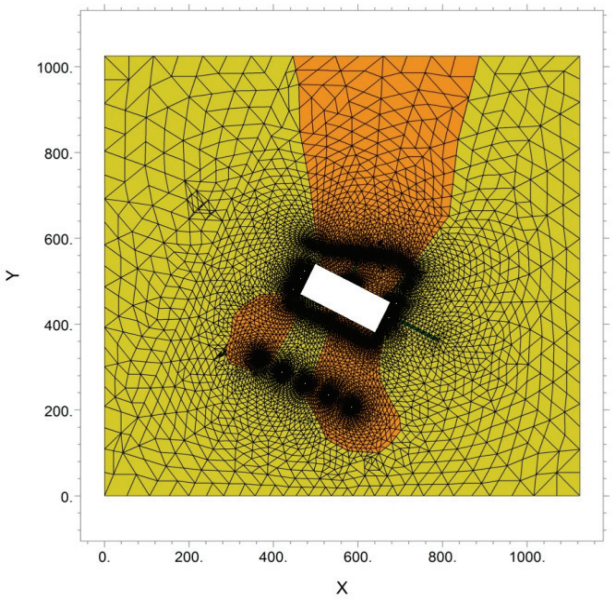


Fig. 4. Finite element grid for area surface

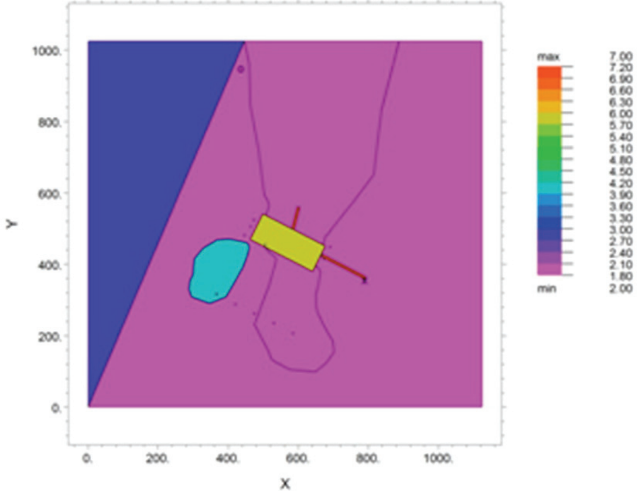


Fig. 5. System of underground layers on 115.6 m level – contact plane between foundation plate and basement (blue –fine sands, yellow – foundation plate, light blue – clay)

The cross-section lines for the reference system introduced were adopted as shown in Fig. 6. The calculation results will be presented along these lines.

The assumed sequence of rock layers in cross-section 6-6' is shown in Fig. 7.

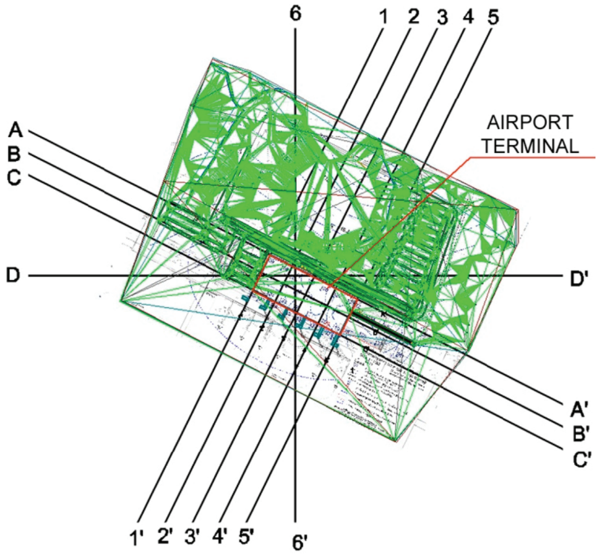


Fig. 6. Cross-section lines assumed for calculations

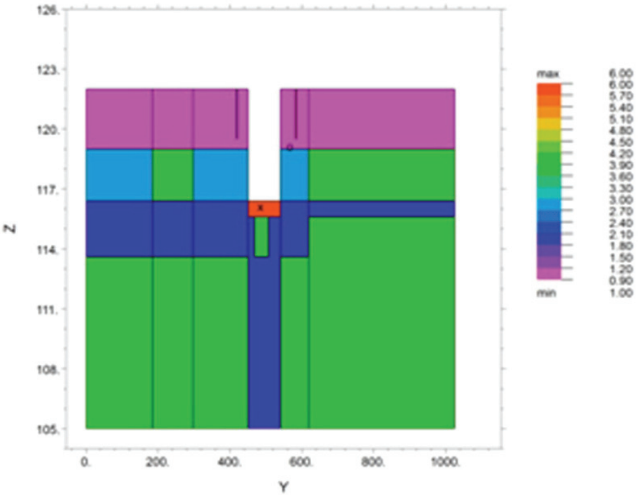


Fig. 7. Sequence of rock layers in cross-section 6-6' (blue – clays, green – Tertiary sands, light blue – loam, red – foundation plate, violet – Quaternary sands)

The calculations covered:

- hydraulic head function $H(x, y)$ for the hydraulic flow model, which also defines the shape of the underground water table for the flow in the Quaternary layer or the surface of piezometric pressures in the Tertiary layer;
- the value of velocity vectors $\vec{v} = (v_x, v_y, v_z)$;
- the yield flowing into the horizontal and vertical drainage

$$Q = \iint_S div(\vec{v})dS \tag{3}$$

For the calculations the model was calibrated through the selection of proper values of permeability coefficients k and infiltration ε for the individual layers.

The water table contour surface, identical for the two aquifers, generated by the MicroStation was taken as the initial value and transferred to the FlexPDE v.6 software. A vertical view of this surface and its three-dimensional picture are shown in Fig. 8 and Fig. 9, respectively.

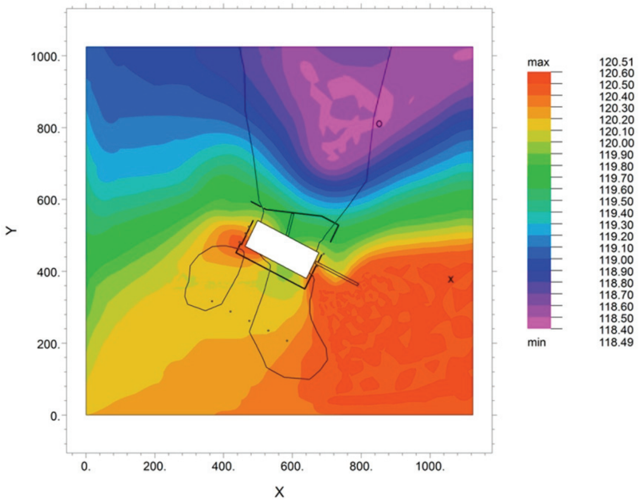


Fig. 8. Vertical view of water table contours for $t = 0$ time (initial condition)

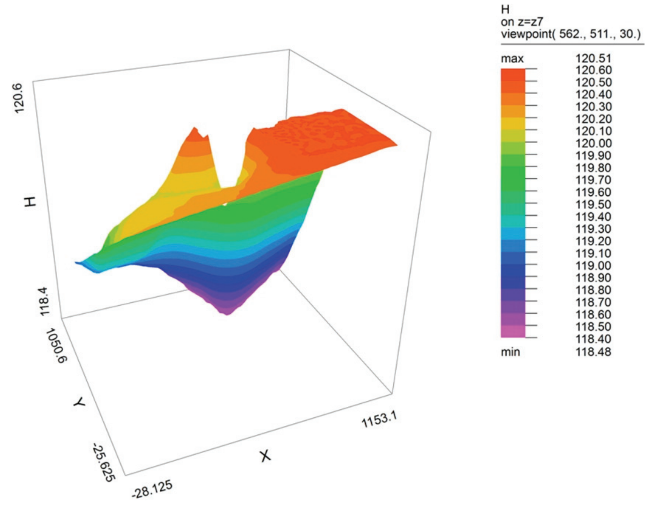


Fig. 9. Three-dimensional shape of underground water table surface for $t = 0$

For the assumed initial underground water table, the calculation program generated the initial vector velocity field shown separately for the Quaternary aquifer and the Tertiary aquifer in Fig. 10 and Fig. 11, respectively.

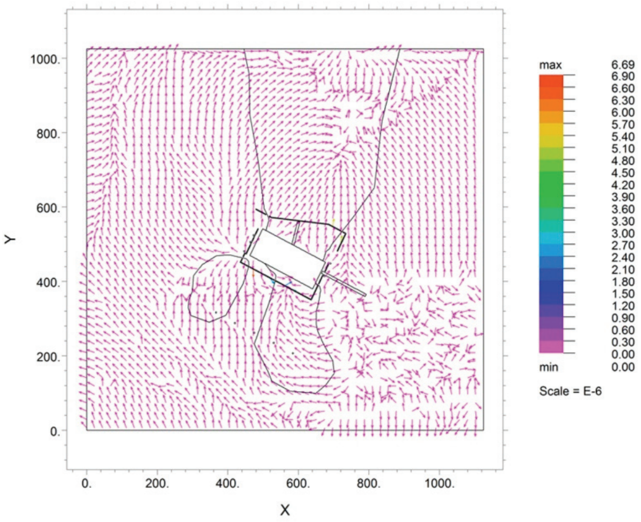


Fig. 10. Vector field projection of filtration velocity on horizontal plane of Quaternary aquifer (vx, vy) for $t = 0$

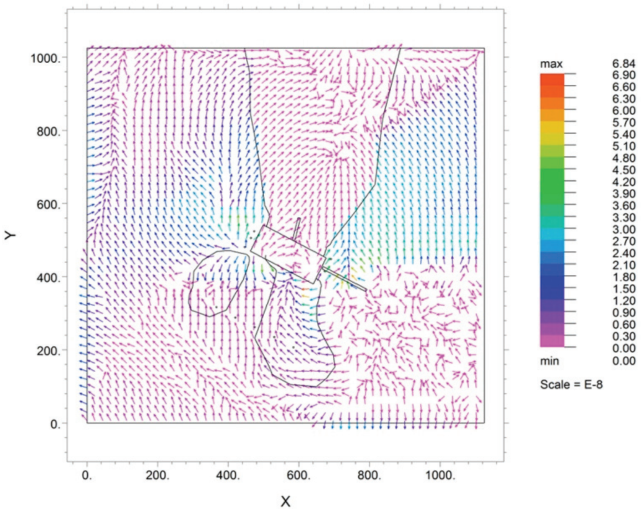


Fig. 11. Vector field projection of filtration velocity on horizontal plane of Tertiary aquifer (vx, vy) under foundation plate of airport terminal, for $t = 0$

Calculation results at instant of starting horizontal drainage

At the instant of starting the horizontal drainage immediate water discharges appear and flow into the drain pipes. Also the effect of initial depression around the drain pipes occurs. Changes in the underground water regime in the Quaternary aquifer take place as shown in Fig. 12.

The changes in the underground water regime in the Quaternary aquifer are not accompanied by any effects in the Tertiary layers, as shown in Fig. 13.

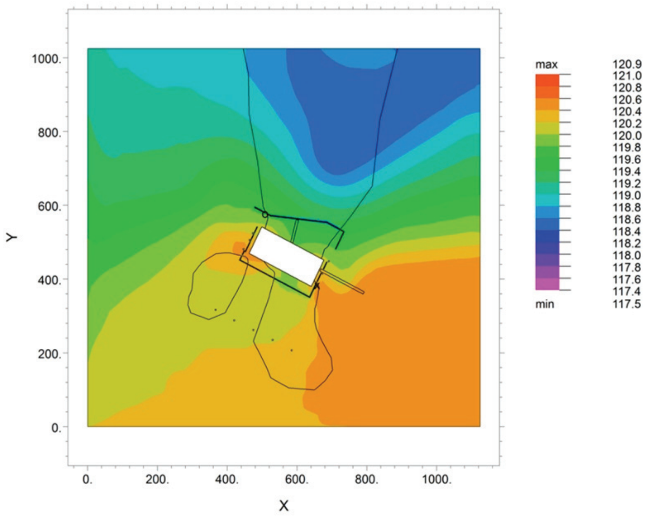


Fig. 12. Water table contours at instant of starting horizontal drainage in Quaternary aquifer

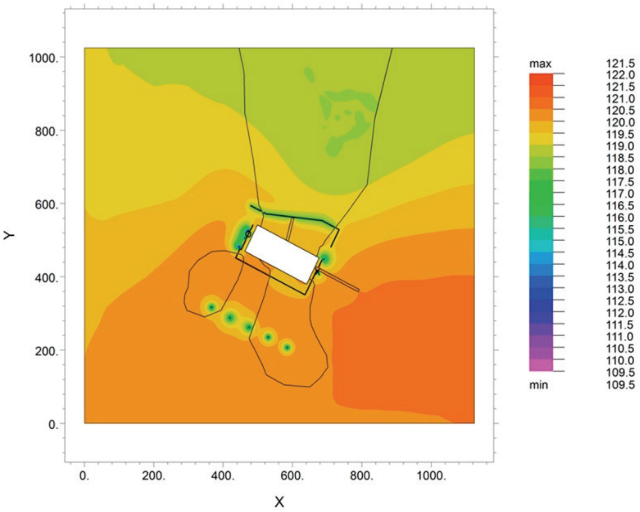


Fig. 14. Water table contours in Quaternary layer after $t = 5$ years

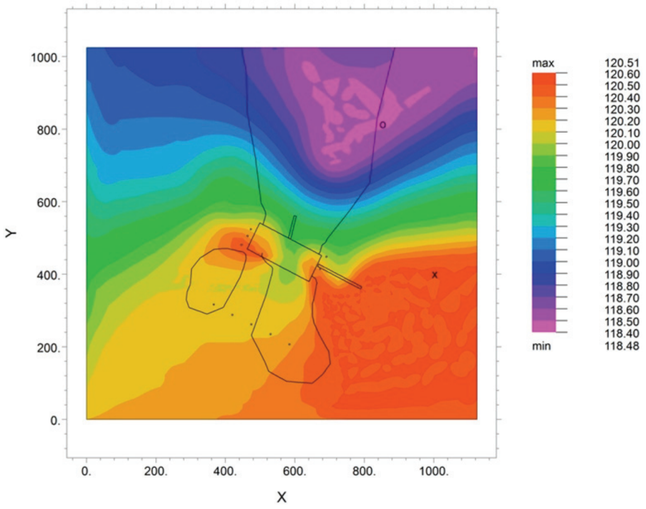


Fig. 13. Water table contours at instant of starting horizontal drainage in Tertiary aquifer

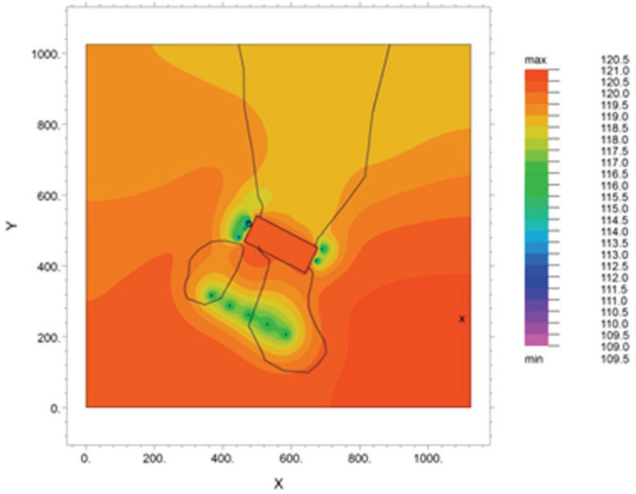


Fig. 15. Water table contours in Tertiary layer after $t = 5$ years

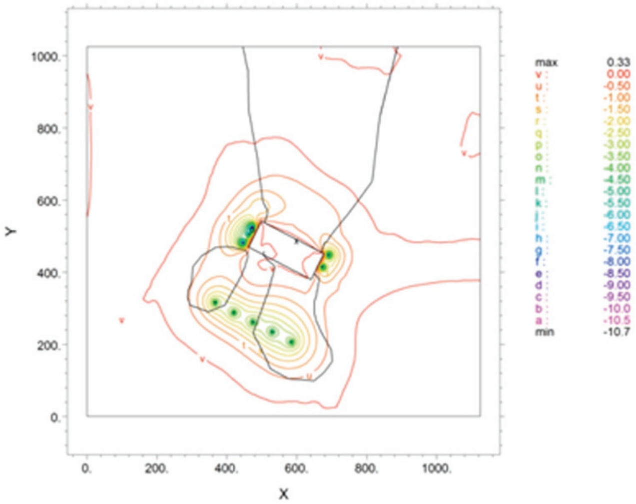


Fig. 16. Water table depression in Tertiary aquifer for $t = 5$ years

Calculation results after five years of horizontal drainage operation and three years of vertical drainage operation

Within the prospective period of time a substantial reduction in the water table in the Quaternary and in the piezometrical pressure surface in the Tertiary layers will occur. The water table contours for the Quaternary and the Tertiary are shown in Fig. 14 and Fig. 15, respectively.

In order to illustrate the depression cone for the two aquifers in relation to the initial groundwater table, the map of water table contours shown in Fig. 16 was produced.

The vector field of filtration velocity can be determined through computer simulations. A projection of vector field filtration velocity on a horizontal plane within the Quaternary aquifer and within the Tertiary aquifer after five years from starting the drainage of the terminal building site is shown in Fig. 17 and Fig. 18, respectively.

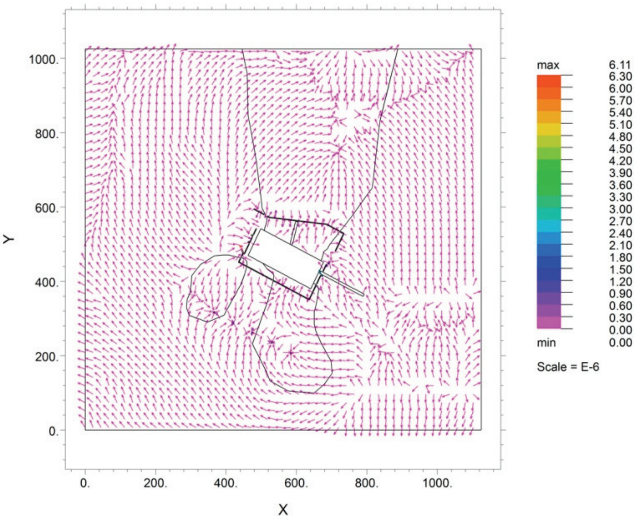


Fig. 17. Vector field of filtration velocity in Quaternary aquifer for $t = 5$ years

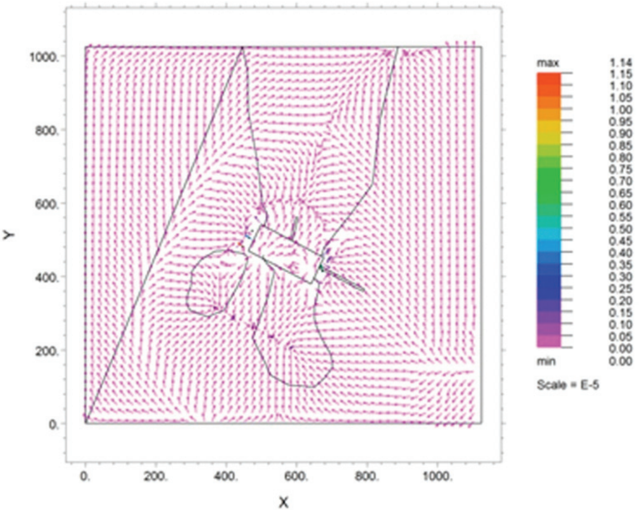
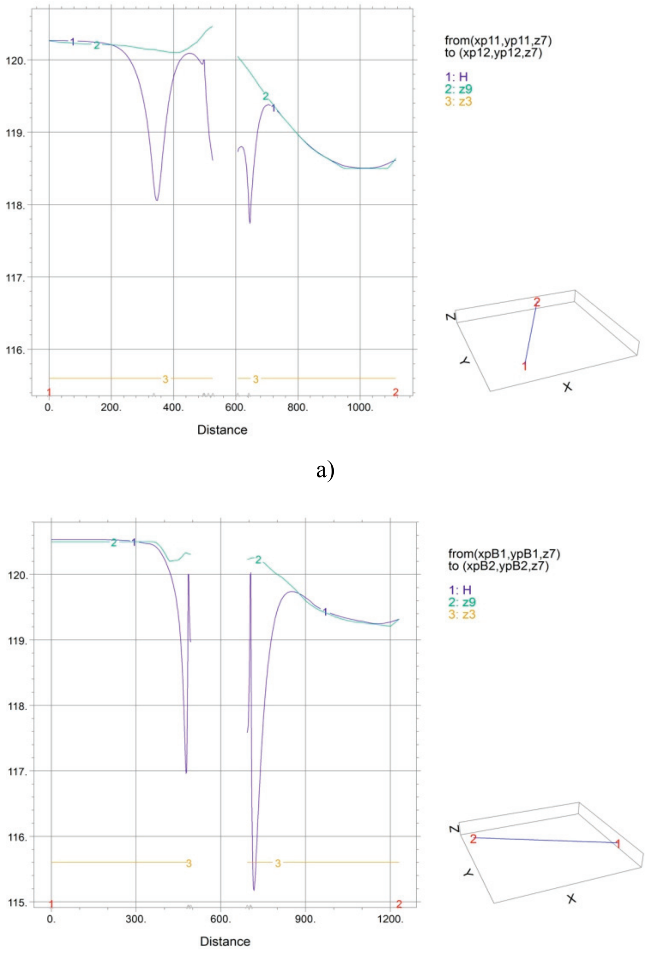


Fig. 18. Vector field of filtration velocity in Tertiary aquifer for $t = 5$ years

Figures 19 and 20 illustrate well the efficiency of the two drainage systems. However, this simulation must be confirmed by measurements carried out in the course of monitoring the drainage process.

Figure 19 shows the water table lines in selected cross-sections for the filtration flow in the Quaternary.



a)

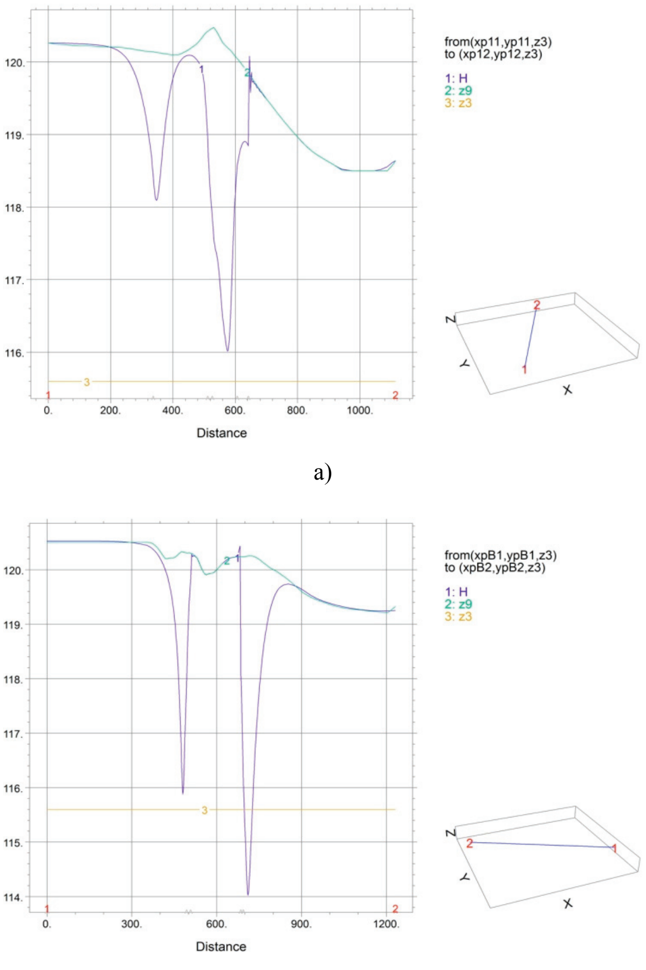
b)

Fig. 19. Water table lines in Quaternary for $t = 5$ years: (a) in section 1-1’, (b) in section B-B’

Figure 20 shows the piezometric pressure lines in selected cross-sections for the filtration flow in the Tertiary sediments.

The charts for the two aquifers, shown in Figs. 19 and 20, are clearly different. It is apparent that the horizontal drainage very strongly affects the Quaternary layer while it has only a small effect on the piezometric pressure line in the Tertiary. Thus it cannot radically influence the measurements in the piezometers under the foundation plate. Much larger pressure reductions are observed in the Tertiary layers. Pore pressure is still high in the clay and silt layers. A substantial reduction in this pressure can be expected to occur after a significantly longer period of time. However, this pressure has no impact on the magnitude of the pressures transferred to the airport terminal foundation plate.

In order to better illustrate the groundwater table in the Quaternary, a three-dimensional chart of the water table was plotted (Fig. 21). A 3D chart of the piezometric pressure surface for the Tertiary horizon is shown in Fig. 22.



a)

b)

Fig. 20. Piezometric pressure lines in Tertiary for $t = 5$ years: (a) in section 1-1’, (b) in section B-B’

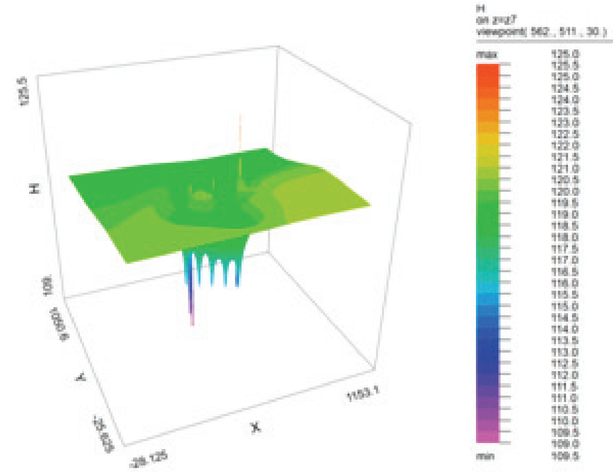


Fig. 21. Prospective water table surface in Quaternary after 5 years of drainage

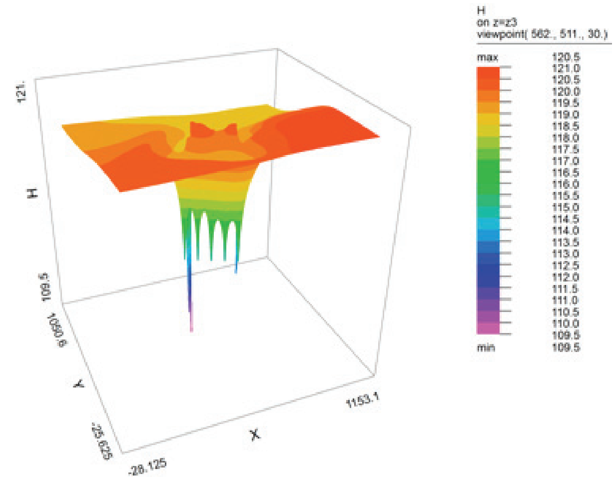


Fig. 22. Prospective surface of water piezometric pressures in Tertiary layer after 5 years of drainage

5. CONCLUSION

The results of numerical calculations for the airport terminal building drainage system for the assumed pumping period of 5 years have been presented. Because of the extremely disadvantageous hydrogeological conditions of the site, it is necessary to use such a system and the results presented show that it is an effective solution to the problem of groundwater pressure on the foundation plate of the building. The drainage of the building was designed in the form of two simultaneously operating dewatering systems: one being a horizontal drainage system consisting of drain pipes laid around the building, aimed at lowering the water table in the subsurface layers and cutting off the water flowing towards the building while the other is a vertical drainage system consisting of ten wells drilled on the east, west and south side of the building, designed to reduce the hydrostatic pressures in the deeper aquifers.

The calculations were based on a good knowledge of the geological structure under the foundation plate of the terminal and in its vicinity as well as in the previously planned location of the terminal. The geology in the remaining part of the area is rather poorly known. For this part, a safe (from the point of view of drainage impact on the environment) assumption that only a sand layer occurs there, was made.

The numerical model of drainage takes into account the complexity of the site’s geological structure. The model can be used to calculate flows for separately horizontal and vertical drainage. The results clearly indicate that the horizontal drainage system has an impact on only the shallow layers and it is the wells that play the key role, being much more effective owing to the relaxation of the airport terminal foundation.

The following conclusions emerge from the analysis of the results:

1. The designed horizontal drainage together with the vertical one will guarantee the effective relaxation of the terminal foundation being under the hydrostatic pressure. The band drainage will reduce the water inflow into the Tertiary layer owing to the smaller infiltration into the building gravel pack, especially during heavy rains and thaws.

2. The depression cone stops developing practically after five years. In cohesive soils the process of porous pressure reduction lasts for a very long time. However, this has no significant bearing on the safety of the construction. If such a drainage level that the hydrostatic pressure corresponds to the water table at the plate foundation ordinate is assumed, there is no risk of any additional subsidence of the building.

3. Measurements of the water column in the piezometers after two years of operation of the horizontal drainage confirm the results of the computer simulations of the airport terminal drainage.

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