Ground water and underground constructions in the City Urban Development

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ABSTRACT: In some underground areas of Belgrade, groundwater may pose a significant problem in the urban development and even more complicate the conditions of construction. Rationally conceived, persistent and purposeful hydrogeological investigations, undertaken within detailed geotechnical works for the purpose of design and construction, are highly important, especially from the aspect of efficient and cost-effective construction, and subsequent safe functioning of the finished structures. If water regime and water balance are not reliably defined in the designing phase, this may cause undesirable effects in the phase of construction and use of underground structures. This paper describes an example of a modern approach to the concept of hydrogeological investigations with results, their objective being to define a well-grounded system of drainage structures in the zone of a water bearing sands for the "Karaburma Desni" tunnel (Karaburma R.H.Tube) in Belgrade (Yugoslavia).

1 INTRODUCTION

All the underground structures in the Belgrade railway junction (tunnel tubes "Banatski desni i levi" /right and left/, "Karaburma levi" /left/) in the area from Bogoslovija to their exit portals in the zone of Karaburma, have required some measures to be undertaken in the construction phase, such as some systems for groundwater table lowering. According to the geotechnical investigations of the detailed design level in the "Karaburma desni" tunnel tube (CIP, 1995) and an additional study of the previous investigation results, a water bearing sand lens was proved to exist from km 0+280 to km 0+450. As the Contractor requested to be allowed to excavate the tunnel in dry, it was necessary to devise and execute some additional investigations, which were planned under a three-phase programme:

Phase I - to determine the basic geometry and sand lens seepage parameters; Phase II - to devise and carry out specific hydrogeological investigations for the purpose of constructing and using adequate drainage systems (wells); Phase III - to construct drainage well systems and lower the groundwater table in the section of the tunnel tube that passes through the sand lens with the permanent monitoring of the works. By the end of Phase I, the contour lines of the sand lens were completely defined, i.e. the geometry and area of the aquifer complex in the wide zone of the tube were determined. Within these investigations, the basic aquifer seepage parameters were studied by grain size analysis and the results of the preliminary tests using new piezometer units were processed.

The groundwater table fluctuations were recorded over a period of only 10 days, which was insufficient for defining the elements of the groundwater balance parameters. Anyway, the recorded piezometric levels, which represented a quasi-steady state, were used for completing the picture about the flow regime of the observed aquifer.

The preliminary hydrodynamic simulation model of the aquifer complex in the sand lens zone was derived from an analysis of the investigation results. In this intermediate phase, the first parameter analyses were done on the model, in order to verify the choice of elements and the effects of the technical variants for the aquifer draining during the tunnelling works. Following this, a Programme of detailed hydrogeological - hydrodynamic investigations was defined, together with the bill of quantities and technical specification for drainage works (investigation/operation) [3].
2 THE CONCEPT AND METHODOLOGY OF PERFORMED INVESTIGATIONS

To meet the conditions for tunnel tube construction in a rational way, it is necessary to devise and realize a certain range of specific hydrogeological investigations. The results of the geotechnical works performed in the Phase I of the additional investigations, the sand lens contours, and a single recording of the groundwater level regime in the existing and newly bored piezometer holes (Fig. 3) became a basis for developing a preliminary mathematical simulation model of the aquifer complex. The basic outlines of the solution were obtained through the parameter analysis, the results of this analysis became a basis for optimization of the scope and kind of works in Phase II.

The preliminary model examinations were used to define a micro-location for a drainage exploratory/operation well, for which a complex pump test was programmed, and the locations for three observation exploratory/piezometric holes. A good quality pump test data processing was aimed at identifying the representative hydrogeological-hydrodynamic parameters and defining the basic conditions for drainage in the wide tunnel zone, and determining the quality of the completed water intake structure. Further in the process of the mathematical model development, these results will be used to finally determine the typical characteristics of porous media built in the preliminary simulation model, and verify the hydrodynamic analyses of the effects of a long-term operation of the drainage well systems.

The objective of such an approach to the hydrogeological investigation concept was to clearly define the optimum and rational technical solution for draining the aquifer complex in the zone of the sand lens, along the axis of the "Karaburma Desni" tunnel tube, according to a precise schedule of works.

3 HYDROGEOLOGY OF THE TERRAIN

The results of interpretation of the additional geotechnical investigations - Phase I [2] helped to define the morphology of the substratum and the roof of the sand lens (Fig. 2), as well as its thickness, in the wide zone of the tunnel. The thickness of the sand lens along the tunnel tube varied from 0.15 to 4.10 m. The sand lens area was defined in the plan, even though the SE and NW boundary lines of the investigated area were not determined. Starting with the flow pattern, done for a quasi-steady state (Fig. 3) it was realistic to assume that this lens did not represent a closed up hydrogeological structure, but a portion of a longish sand interlayer, which, looked from the NE-SW direction, formed an about 200 m wide channel-like restrained body falling towards SW, while from the NW-SE direction, it extended continually in the wide area of investigations.

A subartesian aquifer was formed within the sand lens and was practically delineated with Sarmaitian marls and marly clays from both the substratum and the roof. The existing groundwater regime was analyzed on the basis of observation data which pointed to a practically steady flow in the period of approximately 10 days in the total of 10 new and 4 existent piezometers (Fig.3).

By analyzing these results the constant groundwater migration was encountered, i.e. the steady
BKL-1, BD-1, B-1, MBA, MB-2 were the boreholes and piezometers from the earlier investigations (1977-1995).

BB-7 Drainage wells placed in the period of excavating tunnel 'Banaski' R.H.T.

KB-1 Boreholes for the geotechnical investigations in the process of design (CIP, 1997).

PKB-2 Piezometers for additional hydrogeological investigations (CIP, 1997).

Figure 2. The roof complex and substratum morphology of the investigated sand lens.
groundwater inflow and outflow of the aquifer sand complex.

Some deviations from the groundwater regime were stated in the zone of the retained (former) drainage wells during the construction of the "Banatski desni" tunnel tube. Namely, it was stated on the groundwater level isoline map (Fig. 3) in the zone of the BB-8 well that a local depression was in the process of being formed in the aquifer. This phenomenon was reported to the Investor in the course of Phase I investigations, and the Investor carried out the prospecting work along the "Banatski desni" tunnel tube and stated water seepage into the tube of approximately 5 liter a minute at km 4+447, i.e. in the very zone of the BB-8 well. This fact was proved to be extremely useful in the process of preliminary identification and assessment of seepage characteristics of the concerned aquifer.

Filtration parameters of the aquifer were assessed from the grain-size distribution of the material taken from the sand lens, from ten empirical formulae, and from the graph-analytical processing of piezometer test data. The filtration coefficient values generally varied between $10^{-5}$ to $10^{-4}$ cm/s.

4 HYDRODYNAMIC INVESTIGATIONS

After the Phase I of the additional geotechnical investigations [2], a preliminary mathematical simulation model was formed for hydrodynamic calculations and parameter analyses. The software used in designing the mathematical model of the sand lens, developed and adapted to this specific task, represents the original programme of the Institute for the Development of Water Resources "Jaroslav Cerni", Belgrade (MV36). Using this programme it is possible, in a general case, to find a numerical solution to the Boussinesque differential equation, which describes an unsteady groundwater flow in the analyzed water bearing layer:
\[
\frac{\partial}{\partial x} (K h \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (K h \frac{\partial h}{\partial y}) + Q = \mu \frac{\partial h}{\partial t} \quad \ldots \ldots \ldots \ldots \ (1)
\]

where:

- \( K \) - seepage coefficient, in a general case \( K = K(x, y, t) \)
- \( h \) - piezometric level \( h = h(x, y, t) \)
- \( \mu \) - specific yield (effective porosity) \( \mu = \mu(x, y, t) \)
- \( Q \) - water quantity taken from the aquifer complex \( Q = Q(x, y, t) \)
- \( t \) - time

In the software design and setup for solving the differential equation (1), a modified method of finite elements was used as a basis, and the aquifer complex was discretized into fields of variable length and width. Each field represented one homogeneous unit, with constant geometric and hydrodynamic characteristics in the designed period of time. The modified programme contained an inventive solution to the problem of simulating the transfer from a pressurized flow to a free-level flow (and vice versa). The variations of water permeability coefficient values during the process of assessing the unsteady flow represented, in a certain way, an “introduction” to the model of a spatial flow simulation (which was a plane flow model in the original version). Another specific feature of the applied software lies in some adjustments to it which afford the following realistic possibilities in the process of simulation:

- to lower the simulation model to the size of an arbitrary diameter well (regardless of the size of a discretized field),
- to simulate the lowering of the water level in the wells down to the substratum, and to carry out flow/time calculations for the wells,
- to have a possibility to exclude a discretized field in which the groundwater level is lowered down to the substratum, from the model (and the other way round).

Boundary conditions used in creating the model are known in the literature as Dirichlet and Neuman types. However, these two types cannot by themselves meet all the requirements in solving this problem, so that other types of "boundary" conditions had to be included, these being the genuine software solutions of the author. The boundaries of the mathematical model of the sand lens coincide with the determined and assumed boundaries, obtained from the interpretation of the results of the additional geotechnical investigations - Phase I [2].

With the basic hydrogeological parameters given, the mathematical model of the studied aquifer covered the area of 250 x 150 m (Fig. 5). The basic discretized field of the model was 5 x 5 m.

The parameter analyses were used in the hydrodynamic calculations and forecasts to assess the impact of the following characteristics, not commonly defined in the performed investigations:

- values of the seepage coefficient of the silty sandy lens were within the limits of \( K_f = 1 - 5 \times 10^{-4} \) cm/s,
- the impact of the drainage well diameter variations (Ø 500 - 800 mm),
- the impact of the boundary conditions variations (e.g. as a constant potential at the boundaries and as a constant flow).

In the preliminary model simulation an assumption was made that the aquifer would be drained in a relatively dry period (without any critical infiltration from the terrain surface), and that this may push the calculations to the “unsafe” side, so this fact had to be thought of in the interpretation of the results.

The hydrodynamic forecast calculations, performed on the mathematical model with varying parameters, were made for the large number of (both real and unreal) technical variants of the operation of a series of drainage wells. The calculations were made for the short-time and also the long-time operations of the wells, with different start-up times. Within the parameter analysis the calculations were performed for over 20 variants of different arrangements and working regimes of wells.

To illustrate this, Fig. 5 shows a map of the aquifer thickness (the water column above the substratum) after 45 days of the operation of 6 wells, with the silty sandy lens seepage coefficient of \( K_f = 3 \times 10^{-4} \) cm/s. For the same calculating pattern, Fig. 4 shows changes in the yield of wells during the operation of the designed drainage system and in the water column height above the substratum at 5 points along the tunnel tube axis.

The detailed preliminary model investigations and the performed hydrodynamic calculations needed for the parameter analysis, showed that a number of results and conclusions had to be verified through the Phase II investigations and in operation:

- According to the results of the parameter analysis along a tunnel section where drainage wells were in operation, the residual groundwater column was 1.5 to 2.5 m above the substratum level.
- The absolute residual thickness of the aquifer, i.e. the groundwater column which cannot practically
VARIANT 45/6: 45 days of the operation of 6 wells in the discretized fields 3007, 2707, 2914, 2614, 2917 and 2617

Figure 4. The results and effects of the headwater lowering in the analyzed discretized fields along the 'Karaburma' tunnel axis

Figure 5. The thickness of the drained aquifer (the water column above the substratum) for the analyzed variant with six wells along the "Karaburma desni" tunnel tube after 45 days of operation
be eliminated by wells, depends on the absolute representative value of the seepage coefficient.

- The water quantity that can be evacuated by wells is small (less than a liter per second).
- An increase in the number of drainage structures (wells) need not ensure a proportional drawdown in the sand lens.
- The groundwater level drawdown in the sand lens is efficient in the first 20 days or so, and the later drawdown effects (depending on the conditions of the aquifer recharge) by means of drainage wells may not practically be cost-effective.
- Under the hydrogeological and hydrodynamic conditions given it is necessary to look for an additional drainage method for the purpose of tunnel construction by intended methodology.
- The importance of the well diameters and the quality of their construction is manifested in the size of the residual aquifer thickness of approximately 0.3 to 0.5 m.

5 CONCLUSIVE NOTES

This example of a design of detailed hydrogeological - hydrodynamic investigations intended for draining the terrain in the sand lens zone at the "Karaburma desni" tunnel tube construction in Belgrade, represents one of modern and quality approaches to solving geotechnical problems in design and construction stages of the underground structures in the Belgrade railway junction.

If the particular hydrogeological experiences and hydrodynamic calculations are adequately implemented, especially in the cases where specific problems are due to unfavorable impact of the groundwater table, it will be possible, as early as in the phase of defining the basic design documentation, to arrive at a considerably more effective and more rational approach in solving particular problems and preventing any undesirable effects in the future construction and operation.

REFERENCES

Group of authors, 1997. Project report on additional investigations at the "Karaburma" tunnel (right-hand tube) in the sand lens zone from km 0+280 to km 0+450 - Phase 1 of the geotechnical investigations, Institute of Transportation CIP, Departement of Geotechnics, Belgrade, Yugoslavia

Rasula M., Vukovic M., 1997. A programme of the detailed hydrogeological hydrodynamic investigations to define drainage well systems for the "Karaburma desni" tunnel tube construction, in the sand lens zone from km 0+280 to km 0+450, Institute of Transportation CIP, Belgrade, Yugoslavia


Group of authors, 1995. Project report on additional geotechnical investigations carried out to define shelter construction requirements in the housing projects 8.9 - 8.11 (Block 8) in the S. Penezica street no. 29-31, Institute of Transportation CIP, Departement of Geotechnics, Belgrade, Yugoslavia