Mathematical Modeling of Groundwater Flow – Foundation Piles in the Vicinity of Danube River Case Study

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Abstract

The study investigates an interaction of groundwater flow and foundation piles located in the vicinity of the Danube River. The piles represent an obstacle to the groundwater flow, causing the backwater effect upstream, whilst increasing the local flow velocity. On the other hand, high flow velocity around the piles can cause the suffusion of the surrounding soil in the long term, thus significantly reducing the shaft resistance of the piles. A 3D model of groundwater flow and its impact on the piles was developed in the software package GMS 9.2 based on MODFLOW 2005. It was calibrated by comparing the water level values obtained as a result of the simulations with varying filtration coefficient inputs with the observed values in the monitoring well. After the calibration process, piles were implemented into the model and the underground flow was simulated at the study area location for the calibrated year 2006. The impact analysis was carried out by comparing the groundwater level change over time in the pile zone in three control points, in cases with and without the piles, along with the flow net analysis at the location of the piles themselves. The obtained results indicate an absence of the influence of piles on the groundwater flow at the study area location, both in terms of critical flow velocities and in terms of a possible backwater effect upstream.

Introduction

Groundwater represents the third most abundant component in the global water cycle, along with oceans and snow/glaciers. Groundwater and snow/glaciers comprise more than 97% of all fresh water on Earth (Kim et al. 2020). Moreover, they are one of the most important sources of drinking water, used for various purposes such as agriculture, industry, water supply to the population, etc. (Baki et al. 2017; Xu et al. 2011; Carreira et al. 2018). Groundwater research has been gaining importance in recent years due to the growing awareness of the need for groundwater, as well as the increasing deterioration of its quality and quantity. Numerous issues arising during groundwater research, such as forecasting groundwater level and, consequently, determining the aquifer thickness, have led to the development of various simulation models which describe and predict the groundwater flow (Moghaddam et al. 2019).

Numerical modeling is a powerful tool intended to offer a better understanding of groundwater flow and obtain the information about relevant groundwater parameters. The most important aspect of the use of such models is acquiring data on the real conditions occurring within the observed environment. Namely, such models provide sufficient information for efficient management of groundwater resources (Leake et al. 2005; Mengistu et al. 2015; Yihdego et al. 2015a, b; Yidana et al. 2015). The first step in the modeling process is creating a conceptual model. In the next step, this conceptual model is converted into appropriate mathematical expressions which are combined with boundary conditions to form a mathematical model. Although these models are quite complex and characterized by a large amount of input data, their application is extensive. One of the most commonly used numerical modeling softwares is GMS 9.2 based on MODFLOW 2005, developed by Aquaveo, LLC in Provo, Utah (Mengistu et al. 2019).
A number of authors have used MODFLOW in groundwater modeling for various purposes. Some of them combined it with other models and softwares for more reliable research results. For example, Malekzadeh et al. (2019) estimated the groundwater level using three models: MODFLOW, ELM and WA-ELM. Based on the obtained numerical results from all three models, WA-ELM was proven to be a superior model for groundwater level simulation. El Osta et al. (2018) utilized the Mass Balance Transfer Model (NETPATH), GMS (version 6.5) and DRASTIC model in a GIS environment to assess the groundwater level, as well as to investigate the water-rock interaction. Research was conducted in the areas south and east of the Wadi El-Natrun depression in Egypt. Furthermore, constructed wetlands representing engineering alternatives for decentralized wastewater treatment were analyzed by Fioreze and Mancuso (2019). MODFLOW and MODPATH softwares, based on the finite difference method, were used for the numerical simulation of flow in wetlands. This model was proven to be a powerful tool for 3D simulation, allowing the representation of flow distribution, flow velocities, hydraulic head and particles trajectories. Ibeh (2020) investigated the effect of changing groundwater level on the propagation and continued expansion of gully erosion and landslide in the Odo River sub basin (south eastern Nigeria). The deterministic approach used there is based on the LOCOPSTAB model framework, which combines groundwater recharge model, groundwater flow model (MODFLOW) and slope stability model (Oasys slope). Such a modified approach was aimed at determining the possibility of improving the stability of the study area. Almuhaylan et al. (2020) examined arid regions characterized by groundwater drawdown. A modular three-dimensional finite-difference groundwater flow (MODFLOW) model was applied to a unique aquifer where the impact of different groundwater pumping scenarios on aquifer depletion was evaluated. The study found that the existing pumping rates can result in an alarming drawdown of 105 m in the next 50 years. Furthermore, Chakraborty et al. (2020) used Visual-MODFLOW 2000 for groundwater level analysis in Purba Midnapur area (West Bengal, India). The study was designed to predict groundwater level in future usage scenarios for the purposes of better groundwater management. La Licata et al. (2018) conducted a hydrogeological study to find out the cause of groundwater flooding. The flow model was calibrated for steady and unsteady-state using the automatic calibration code Model-Independent Parameter Estimation (PEST). Khalaf and Abdalla (2014) in their research described two overlaying aquifers in Farafra Oasis and represented a typical hydrogeological model of a vast multi-layered artesian basin extending over the territory of Egypt. The rapid drilling process in the 1960s caused many springs and wells to dry up. It was thus concluded that there is a real danger of either dewatering or increasing the water depths to uneconomic lifting depths for both shallow and deep aquifers. In order to solve the problem, a two-dimensional GMS model was used. Lutz et al. (2007) developed a conceptual groundwater flow model for a hydrographic basin of northern Ghana to address the sustainability of groundwater resources. A three-dimensional, steady-state model was applied to the Nabogo basin, a sub-catchment of the White Volta River Basin. The model showed that the current well pumping rates are lower than the annual groundwater recharge to the basin. To evaluate the groundwater resources and aquifer system of the Jilin urban area (JUA, China), Qiu et al. (2015) established a numerical groundwater flow model using GMS, based on the data from 190 boreholes. Recharge proved to be the most sensitive factor in this model. Based on the supply and demand analysis of water resources, the developed model could finally provide a scientific basis to use the groundwater resources sustainably in JUA. In their study,
Aghlmand and Abbasi (2019) modeled the Birjand aquifer (Eastern Iran) using GMS:MODFLOW to monitor the groundwater status in the Birjand region. The results of the model were in good agreement with the observed data and, therefore, the model could be used for studying the water level changes in the aquifer. Wondzell et al. (2009) addressed the questions of how reliable hyporheic groundwater models are in typical applications examining such flow exchanges and how reliability changes with increased data availability and model sophistication. The increased model sophistication was shown not to lead to improved model reliability as the travel time predictions from the homogeneous model were equal to, or better than, the predictions from the heterogeneous models. Li et al. (2019) analyzed the connection between shallow groundwater and vegetation growth, which is on the whole very close. The first conclusion was that the water table and salinity can be identified as the main factors controlling shallow groundwater. Secondly, regulation plans for water table and salinity were designed based on the corresponding regulation target and finally, the output results from the software runs could provide the information on how to regulate shallow groundwater in different scenarios.

The primary goal of this paper is to gain insight into the interaction of groundwater flow and foundation piles located near a river by means of a 3D numerical model described below. The findings suggest that the piles represent an obstacle to the groundwater flow, causing the backwater effect upstream, whilst increasing the local flow velocity. On the other hand, high flow velocity around the piles can cause the suffusion of the surrounding soil in the long term, thus significantly reducing the shaft resistance of the piles.

**Materials and methods**

**Study area**

The location of the study area is situated in Novi Sad, the Republic of Serbia (Fig. 1). The principal issue of the location is the proximity of the levee and, consequently, the prospective adverse impact of the structure at the location on the groundwater flow and, thus, on the stability of the levee. Since the structures at the study area location are founded on piles, the piles in the soil represent a unique type of hydraulic obstacle from the aspect of groundwater flow which can result in the alteration of the flow pattern at the location positioned at a relatively short distance from the Danube River. This flow modification caused by the grid-type obstacle can produce a rise in the groundwater level in the vicinity of the structure on the one hand, as well as a deformation of the steady-state flow pattern at the location caused primarily by the proximity of the Danube on the other hand. The influence of the immediate vicinity of the Danube on the structure is reflected primarily in the "practically" direct connection of the water flow and its dynamics with the site. The change in the hydraulic regime in the Danube due to its proximity is relatively quickly "transferred" to the study area location, which is why this pile "structure" can significantly affect the groundwater regime both in terms of the level and in terms of flow rate in the porous medium. A sudden rise in the Danube level generally generates significant hydraulic gradients in the soil located in the close vicinity of the contact with the Danube, which inevitably leads to an increase in filtration rates. An additional reduction in the flow profile can result in an additional intensification of
filtration rates at the location, which can certainly threaten the integrity of the soil around the structure itself and in its surroundings. Taking the proximity of the levee into account, it becomes clearly evident that carrying out an adequate estimation of groundwater flow at the location is necessary to determine the impact of the structure on the groundwater regime and propose appropriate measures to eliminate negative effects. Considering the complexity of the issue from the aspect of the structure itself, where the foundation was made using piles of different lengths, and in terms of the proximity of the Danube and the influence of its hydraulic regime which is primarily characterized by temporal variability, the above-mentioned analysis can be conducted exclusively by applying an unsteady-state spatial mathematical model of water flow in a porous medium which is able to model such complex conditions.

Methodology

The Groundwater Modelling System, GMS 7.1, was chosen for the conceptualization and numerical modelling. This software package incorporates the United States Geological Survey’s Modular three-dimensional Finite Differences groundwater flow code, MODFLOW-2000, the Finite Element code, FEMWATER, and several solute transport codes. Hence, there is an opportunity to choose from a variety of codes, depending on the available data and the objectives to be achieved. Both numerical groundwater flow modelling codes, MODFLOW and FEMWATER, are flexible to use in the GMS system. In this study, MODFLOW was chosen for the numerical simulation since it has been universally very well tested to simulate similar conditions in other places around the world. Basic description of the case study area is presented in previous section. Details of the case study area in line with the GMS model framework are presented below.

Conceptual model

The first step in building the conceptual model is defining the dimensions of the modeled area. The data used for this were those on available boreholes and levels of the Danube River. Defining the dimensions of the area primarily refers to determining the area within which the calculations will be carried out. Defining the boundaries of the model is directly determined by the sites where the available data on the measured levels are located, which as such are implemented in the model in the form of boundary conditions. In this case study, the layout plan of monitoring wells was obtained from The Urban and Spatial Planning Institute of Novi Sad, Fig. 1. The modeled area was formed by connecting the boundary wells S-73, S-112, P-14, S-26 (well S-102 was used for calibration purposes) and the Danube, thus generating a closed polygon within which a grid was formed and simulations were performed. At the well locations and the Danube, corresponding level measurements were set as boundary conditions. Interpolation was performed for each moment in time on the parts of the outline between the wells. After defining the dimensions of the model, the grid was formed. As this section is significantly larger than the case study area, the approach of different grid resolutions was chosen for the grid formation. Namely, as the structure itself and its immediate surroundings require more attention to detail, a denser grid was used at this site - a higher resolution in the surface area of 50.0x50.0 m, while a lower resolution grid was applied for the remaining area - the grid containing the cells with dimensions 10.0x10.0 m (Fig. 2a). As the structure at the location is founded on piles with different diameters (0.6–0.8 m), the principle
of local grid densification was used for the purposes of modeling these elements. This procedure involves increasing the grid resolution only at the location of the case study element (i.e. the pile), while in its immediate vicinity the resolution is gradually reduced until the resolution set in the broader region is reached. The broader region contains the grid cells with dimensions 10.0x10.0 m, while a higher resolution was used in the zone around the structure itself and a cell of 0.5x0.5 m was set for the section next to the piles. The obtained grid at the location of an individual pile was of such resolution that it was possible to replace one pile with several grid cells and, thus, simulate its influence on the groundwater flow at the location of the study area.

In the vertical direction, four grid layers were set to adequately cover both the height position of the impervious area and the dimensions of the piles in the vertical view. The diameter of all piles is 80 cm, while their length varies in the range of 9–13 m. The first layer extends from the surface of the terrain to an elevation of 77.46 m, the second in the range 77.46–74.94 m, the third covers 74.94–65.94 m, and the fourth one is in the region 65.94–58.00 m. For each of these layers, corresponding values of hydraulic parameters - the filtration coefficient K and retention coefficient S - along with the parameters describing the permeability and yield of the soil were used. The disposition of the considered layers of the analyzed area is shown in Fig. 3.

Model calibration

For the previously defined model, model calibration process was initiated in the next step. This procedure involves the variation of the above-mentioned hydraulic parameters for a simulation time period followed by the comparison of the obtained results with certain available measurement points within the boundaries of the model itself. The main goal is to obtain the best possible match between the calculated and observed values. In order to reproduce the groundwater regime at the given location as accurately as possible and then determine the potential impact of the structure on the state of the waters, the entire year 2006 was taken as a simulation period. Namely, transient simulation was carried out for 2006 as it is the year with extremely high water level recorded at the hydrological station Novi Sad. For these purposes, a temporal change of the piezometric head was specified in the wells located on the boundaries of the model, and the water level graph for the year 2006 was specified on the boundary line between the modeled area and the Danube (Fig. 4).

The calibration process was carried out by comparing the water level values obtained as a result of the simulations with varying filtration coefficient inputs with the observed values in well S-102. It was done without the pile structure, i.e. the structure was not applied in the model during the calibration process. For the model defined in this way, the filtration coefficients \( K = 250.0 \text{ m/day} \) and the retention coefficient \( S = 0.005 \text{ 1/day} \) were determined. The comparison of the calculated and observed water levels in well S-102 for the entire simulated period of the year 2006 is presented in Fig. 5. An example of the spatial distribution of the groundwater level is shown in Fig. 6, along with the detail of the structure showing three control points - KT-1, KT-2 and KT-3 - located at a distance of 3.5 m from the structure itself, which can provide assistance in comparing the temporal distribution of the groundwater levels for the year 2006 and for the two cases, i.e. with and without the structure. In this way, the impact of the structure on the
groundwater levels in its vicinity can be monitored, including the periods with the transient state of the Danube regime and, thus, of the groundwater regime for 2006.

Results and discussion

After the model calibration, the structure was implemented into the model according to the available layout plans and the groundwater flow on the case study location was simulated for the calibrated year 2006. Each of the piles was individually inserted into the model using the principle of "blocking" the grid cells inside the pile to the depth of 9–13 meters, practically forming a no-flow zone at the position of the pile itself. For the study area location as described above, shown in Fig. 2b in the form of cells in the horizontal plane, the impact of the structure on the groundwater in the surrounding area was analyzed by comparing the groundwater level change over time in three control points - KT-1, KT-2 and KT-3 - in cases with and without the structure, as well as by examining the flow net at the location of the structure itself. Comparison diagrams for each of the control points are given in Fig. 7, while the maximum velocity values for the cases with and without the structure, along with an example of the resulting flow net for March 9, 2006 are shown in Figs. 8, 9 and 10, respectively.

The obtained results indicate a complete absence of the influence of piles on the groundwater flow at the study area location. If numerical oscillations of the level in the control points from April to May are excluded, the diagram lines of groundwater level change are nearly coincident for the cases with and without the structure. These oscillations are solely a consequence of the process of drying and wetting of cells and layers due to the temporal variation of the groundwater level. This process is numerically accompanied by minor oscillations of the level as a result of permanent wetting and drying of cells. This congruence of results primarily suggests that the structure itself does not in any way affect the groundwater levels both in its immediate surroundings and in the broader region around it. On the other hand, the diagram of the maximum flow velocity values shows a slight increase in velocities in the space between the piles, i.e. along the lines of the shortest distance between two piles (Fig. 9). However, the analysis of the maximum velocity values clearly demonstrates that there is only a slight (negligible) increase in the velocity in the zone between the piles. Therefore, when observing the case without the structure (Fig. 9a), it can be noticed that the maximum velocity values amount to around 0.35 m/day, while in the case with the structure they reach the value of 0.40 m/day (Fig. 9b).

Conclusion

The paper presents mathematical modeling of groundwater flow in an area containing piles. Due to the complexity of the flow pattern caused by the proximity of the Danube River and the stratification of the soil, as well as a rather dense distribution of piles at the study area location, a 3D model of water flow in a porous medium was used. The applied principles included local grid densification and the formation of no-flow zones in the positions of the piles themselves. The impact analysis was carried out by comparing the groundwater level change over time in the immediate vicinity of the piles in three control points, along with the flow net analysis in the pile zone. The built model was first calibrated based on the available
measurements, and then a simulation of the flow in the pile zone was carried out. The obtained results indicate an absence of the influence of piles on the groundwater flow at the study area location, both in terms of critical flow velocities and in terms of a possible backwater effect upstream.

References


Figures

Figure 1

The modeled area in the broader region of the study area
Figure 2

Display of the accepted grid a lower resolution of the broader region, b higher resolution around the structure itself
Figure 3

The disposition of the considered layers

Figure 4

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