Modeling of groundwater lowering in multi-aquifers area

Modélisation de l'abaissement des eaux souterraines dans une zone d'aquifères multiples

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ABSTRACT

Groundwater lowering is a necessity for underground construction works, especially in urban areas where groundwater exists. Economical design of dewatering schemes requires a thorough understanding of the different modeling tools that are capable of predicting the behavior of dewatering systems. This study presents the results of a three-dimensional (3-D) numerical analysis of in-situ pumping tests that were carried out in a multi-aquifers area. Comparison between the numerical results and the monitored responses of the carried out pumping tests are presented to exhibit the adequacy of the proposed numerical scheme. In addition, the necessity of using numerical modeling for complex site conditions was delineated through the analysis of a dewatering system of a large excavation that was required for a culvert construction in the considered multi-aquifers area where the pumping tests were carried out.

RÉSUMÉ

L'abaissement de la nappe phréatique est une nécessité pour les travaux de construction souterrains, en particulier dans les zones urbaines, où les eaux souterraines existent. La conception économique des systèmes de rabattement de la nappe exige une compréhension approfondie des différents outils de modélisation qui sont capables de prévoir le comportement des systèmes d'abaissement des eaux souterraines. Cette étude présente les résultats d'analyse numérique à trois dimensions (3-D) des essais de pompage in-situ qui ont été menées sur une zone d'aquifères multiples. La comparaison entre les résultats numériques et les résultats des tests de pompage effectués sont présentés pour montrer la pertinence de schéma numérique proposé. En outre, la nécessité de l'utilisation de la modélisation numérique pour des conditions de site complexes a été montrée par l'analyse du système de rabattement des eaux souterraines d'une grande excavation pour la construction d'une galerie d'eau dans la zone d'aquifères multiples où les essais de pompage ont été effectués.

Keywords: Groundwater, modeling, aquifer, numerical, three-dimentional.

1 INTRODUCTION

The impact of groundwater on underground construction projects is enormous. Groundwater affects the design of the structures, the construction procedures and the overall project cost. Analysis of dewatering systems is mostly carried out using analytical or numerical models. The analytical models consider simplified assumptions to represent the in-situ characteristics of geologic formations. These formulas were bisacally developed by Thiem (1906) and Muskat (1937). A good review of these formulae was reported by Mansur and Kaufman (1962), Hausmann (1990) and Powers (1992). These models consider single homogeneous, isotropic aquifers of infinite extent with straight boundaries, rectangular strips, perfectly circular excavations, and sudden drawdown (Theis 1935, Bruggeman 1999). Some analytical solutions of Jacob (1946), Hantush (1965) and Hantush (1966) address issues such as semi-confined or leaky conditions but they always assume a homogeneous system. More recent contributions (Barker 1988, Butler 1988, Butler 1991 and Butler 1993) have provided analytical solutions that deal with a complex aquifer by dividing it into several regions of homogenous properties. However, the analytical solutions can not consider many regional hydrologic features that affect groundwater flow such as aquifer anisotropy, structural features and recharge (Ardito et al. 2004). Analytical solutions of transient flow problems are even more troublesome to analyze, because they often require tables, graphs, or mathematical evaluation of complex functions. The usage of the analytical equations to analyze groundwater flow systems assumes the validity of the cumulative/superposition technique which can theoretically be applied only when all hydraulic properties and boundary conditions remain constant during pumping. Therefore, complicated flow problems can not be solved by analytical methods. Numerical models of groundwater flow problems possess the ability to overcome the limitations associated with the usage of analytical models. Numerical analyses using either finite difference technique or finite element method, were implemented to solve groundwater flow models. Computer packages of the finite element programs (Brinkgreve 2003) and the finite difference programs (Harbaugh and McDonald 1988) are widely used in numerical analysis of groundwater flow problems. Simulation of groundwater flow impacts due to a pumping well back to Pinder and Bredehoeft (1968) were an axisymmetric numerical model designed for a well-test interpretation. Many other efforts focused on developing numerical models that investigated well-test interpretation, pumping impacts and the impact of heterogeneity upon the uncertainty of the interpreted results (Cooly 1971, Lachassagne 1989, Herweijer 1996 and Meier 1998). Numerical groundwater models were found to be the most appropriate tool that allows simulation of complex three dimensional dewatering problems which contain gravity or mixed aquifers, soil anisotropy, partially penetrating wells, vertical boundaries, vertical flow…etc (Powers et al. 2007). This study presents the results of a three-dimensional numerical analysis of in-situ pumping tests that were carried out in a mixed aquifer area. A comparison between numerical results and monitored responses recorded during the different pumping tests are presented to evaluate the adequacy of the proposed numerical schemes. Also, the paper presents the analysis of a dewatering system

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required for construction of a wide long underground culvert that was supposed to be constructed in the area where the pumping tests were carried out.

2 SITE CONDITION AND PUMPING TEST DESCRIPTION

The pumping tests considered in this study were carried out in El-Gabal El-Asfar area, located near the north west boundary of the Cairo governorate. The soil formation at the location of the pumping tests consisted of a surface layer of fine to medium sand with some fine gravel and traces of silt, 4.1m thick. The surface sand layer was underlained by a very stiff brown silty clay layer, 10m thick, extending to a depth of 14.1m below ground surface. The clay formation was followed by a fine to medium very dense sand layer which extended to the end of the carried out borehole, 40m below ground surface. A group of piezometers were installed to monitor the groundwater level. At each piezometer location a shallow piezometer and a deep piezometer were installed to monitor the groundwater level in the top and bottom sand layers, respectively. Piezometers were constructed along two perpendicular lines, denoted A and B, as shown in Figure 1. Six piezometer sets were installed along line A and eight piezometer sets were installed along line B. The piezometers readings showed that the groundwater in the top sand layer was at 2.1m below ground surface while it was at 3.1m below ground surface in the bottom sand layer. This soil stratification and groundwater conditions at the considered site represent a multi aquifers area consisting of a top unconfined aquifer and a bottom confined aquifer.

A deep well, 25m length, was constructed at the point of intersection of lines A and B as shown in Figure 1. The well pipe was slotted except the top 1.0m and the bottom 1.5m. Firstly, a pumping test was carried out by pumping the deep well at a constant discharge rate of 100 m^3/hour, pumping test (1).

After completion of pumping test (1), a group of sand drains, shown in Figure 1, were constructed along line B to connect the upper and the lower sand formations. Sand drains extended from the ground surface to a depth of 6.0m below the bottom of the clay layer. Each sand drain hole was 400mm in diameter containing a slotted PVC pipe, 100mm in diameter. The space outside the slotted PVC pipe was filled with a graded coarse sand and fine gravel filter. The pumping test was then repeated at a discharge rate of 100m^3/hr to investigate the sand drains effect on the groundwater follow regime. In the following discussion, this pumping test is referred to as pumping test (2). A few deep piezometers A_5, A_6, B_4 and B_7 were, later, destroyed by mobile construction equipments.

3 NUMERICAL MODELING SCHEME

Numerical modeling in the current study was carried out using the groundwater flow code MODFLOW that is based on the finite difference concept (Harbaugh and McDonald 1988). A three-dimensional numerical model for the considered mixed aquifers was established to investigate the groundwater flow regime during pumping. The numerical model considered an area of 2000m × 2000m in plan. The area was divided into a grid of cells consisting of 180 rows and 180 columns. The cells ranged in size from a minimum of 5 m to a maximum of 40 m. The vertical depth of the model domain was 55 m and it was divided into 16 stacked layers, of thickness ranging from 2 to 4m. The pumping well was located at the center of the

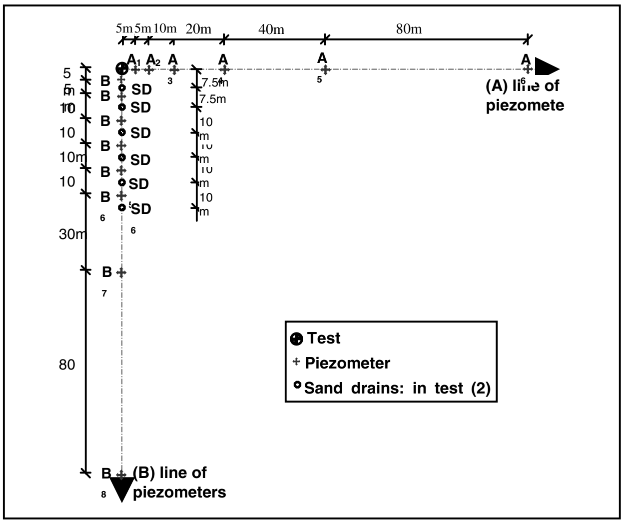

Figure 1. Layout of the pumping tests: test (1) without sand drains and test (2) with sand drains.

considered area. Each soil layer in the model was considered to be uniform, homogenous and isotropic. Table 1 exhibits the hydraulic parameters adopted in the current study for different formations. The considered hydraulic conductivity of sand drains was 0.01 m/sec.

Table 1. Hydraulic parameters adopted in the numerical analysis:

Parameters	Top aquifer	Clay	Bottom aquifer
Hydraulic conductivity (m/sec)	4×10^{-4}	4×10^{-9}	3×10^{-4}
Specific yield (Sy) (m^{-1})	0.20	--	--
Specific storage (Ss) (m^{-1})	--	--	0.001
Effective porosity ($n_{eff.}$)	0.35	0.55	0.35

4 ANALYSIS RESULTS AND COMPARISON WITH FIELD MEASUREMENTS

The established numerical model was used to predict groundwater drawdown during the two pumping tests, pumping test (1) and pumping test (2). The results are discussed in the following sections.

4.1 Pumping test (1)

The values of groundwater drawdown in the bottom sand formation were monitored at the piezometers locations and are presented in Figure 2. A negligible drawdown values, less than 0.05m, were detected in the shallow piezometers. This implies that the flow to the well from the top sand aquifer is insignificant. Figure 2 exhibits also the numerically predicted groundwater drawdown values within the bottom sand formation. A good comparison is delineated between the numerically predicted drawdown values and the in-situ readings of groundwater drawdown within the bottom sand formation, which ascertain the adequacy of the established numerical scheme.

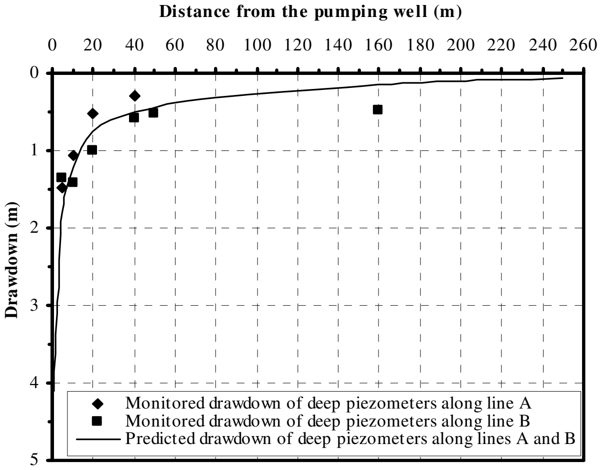

Figure 2. Comparison of monitored and predicted drawdown values within the bottom sand aquifer, pumping test (1).

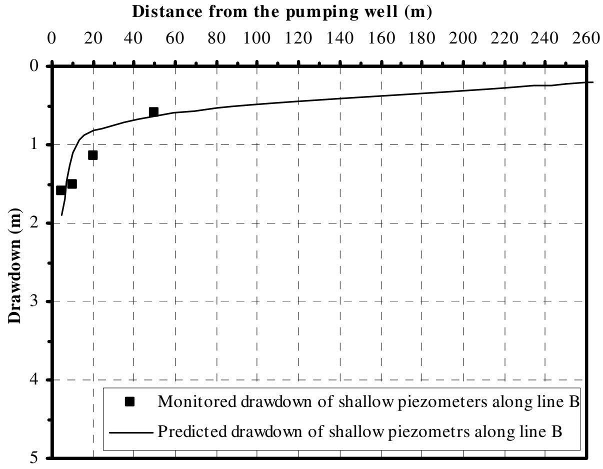

Figure 4. Comparison of monitored and predicted drawdown values within the top sand aquifer, pumping test (2).

4.2 Pumping test (2)

The steady state drawdown configuration in the bottom aquifer is shown in Figure 3, after constructing the sand drains along a part of line B near the pumping well. Figure 3 exhibits, also, the numerically predicted drawdown along line B. A good comparison is delineated between the monitored and the predicted drawdown values. The maximum predicted drawdown value in the bottom sand formation, near the pumping well, was around 3.8m. Figure 4 compares the drawdown values, monitored at the working shallow piezometers locations, and the predicted values along line B. A reasonable comparison is exhibited between the monitored and the predicted drawdown values. In addition, Figure 4 exhibits that a significant drawdown value, reaching about 1.7m near the well, was achieved in the top sand formation in comparison with around 0.05m during the pumping test (1). These results confirm the effectiveness of using sand drains to lower the groundwater of the top sand layer in the considered area. Both Figures 3 and 4 delineate the adequacy of the proposed numerical scheme in modeling groundwater flow in the complex mixed aquifer system at the area under consideration.

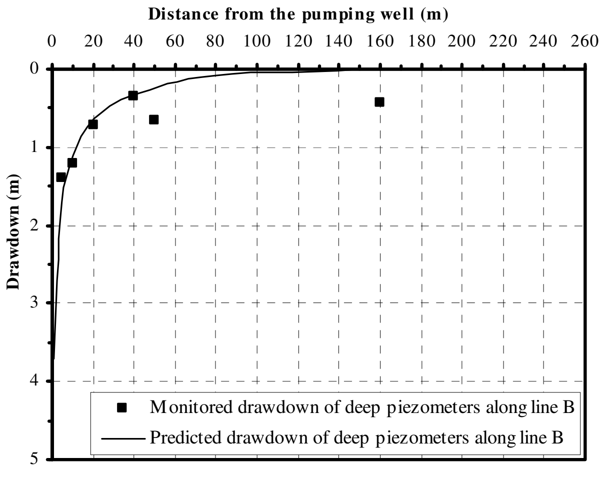

Figure 3. Comparison of monitored and predicted drawdown values within the bottom sand aquifer, pumping test (2).

5 CONSTRUCTION DEWATERING FOR AN UNDERGROUND CULVERT

The success of numerical analysis in simulating the in-situ behavior of the considered pumping tests, render it as a reliable design tool for design of the dewatering systems. A three-dimensional numerical model was established to numerically analyze a dewatering system necessary for construction of a section of an underground culvert in the area where the pumping tests were carried out. Figure 5 illustrates the cross section of the required excavation for construction of a typical sector of the culvert. The excavation base dimensions, at a depth of 10.35m below the ground surface, were 12m in width by 100m in length.

The proposed dewatering system should be adequate to prevent water flow into the excavation from the top sand aquifer and to reduce the uplift groundwater pressure of the bottom sand aquifer on the bottom surface of the clay layer such that the factor of safety for the stability of the clay layer is greater than 1.2.

The proposed dewatering system for the culvert construction consisted of deep wells, 25m in length, similar to that used in the pumping tests, that were installed on the longitudinal sides of the culvert excavation at spacing of 20m, center to center. The distance between the excavation centerline and each of the well lines was 25.0 m. A sand drains line was constructed parallel to each well line. Sand drains lines were 2.5m out of the well lines. The sand drains were constructed at a spacing of 5m, center to center. To optimize the design of the proposed dewatering system, numerical analyses were carried out to investigate the effect of the well length and spacing of the sand drains.

5.1 Numerical Analysis Results

Dewatering analysis of the considered excavation and site conditions was relatively complex due to the existence of two aquifers that were connected by sand drains. Use of analytical equations for analysis of such conditions would result in an approximate solution for such configuration. Three dimensional numerical analysis of the dewatering system was carried out assuming a discharge rate of 60 m^3/hr for each well. The

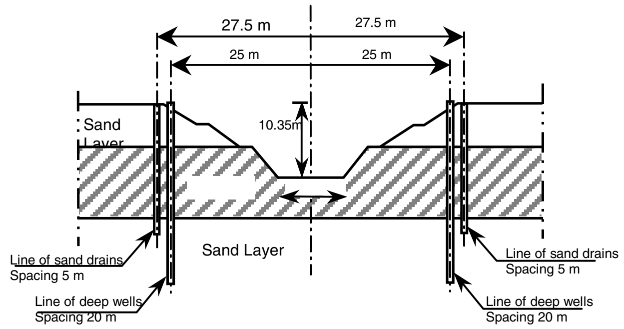

Figure 5. Excavation configuration required for construction of the typical culvert sectors.

drawdown value achieved at the excavation center was 6.2m. which fulfills the construction requirements concerning groundwater drawdown and stability of the clay layer.

Figure 6 exhibits the predicted drawdown values within the top and bottom aquifers. The figure exhibits that the drawdown values are equals at the excavation center while differ at nearly 27m away from sand drains location. In other words, the effect of sand drains in connecting the two aquifers is confirmed at the excavation area.

When the well length was increased to 30 m, the analysis results exhibited a drawdown of 5.3 m. Hence, using a well length of 25 m was found to be more efficient and economic than longer wells.

The effect of sand drains spacing on the drawdown at excavation centre is delineated in Figure 7. When the spacing between sand drains increased to 10 m and 20 m, the drawdown at excavation center decreased to 5.8 m and 5.1 m, respectively. In other words, decreasing the spacing between sand drains increases the drawdown at the excavation centre.

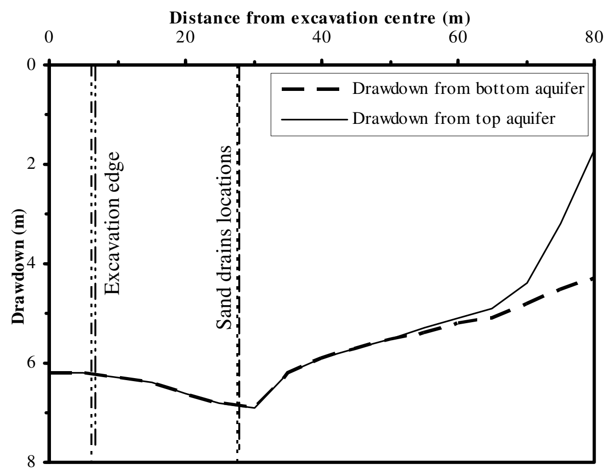

Figure 6. Comparison between the drawdown values predicted from top and bottom aquifer.

6 SUMMARY AND CONCLUSIONS

In The current study presented the results of a three-dimensional numerical analysis of in-situ pumping tests that were carried out in a mixed aquifer area. Good agreement was found between the numerically predicted values and the in-situ measurements of groundwater drawdown values for the considered pumping tests. In addition, the necessity of using numerical groundwater models to design complex dewatering

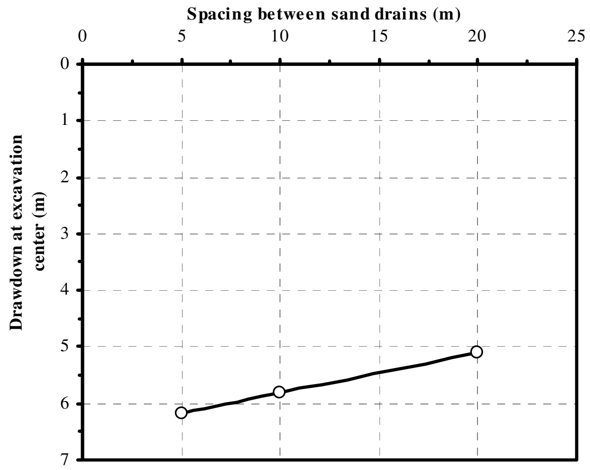

Figure 7. Effect of sand drains spacing on the drawdown at excavation center

problems was delineated through the analysis of a dewatering system required for construction of an underground culvert at the considered mixed aquifer area. The following conclusions were reached:

(1) Simulation of groundwater flow using numerical modeling is recommended to solve complex dewatering problems that can't be solved by the equilibrium formulae.
(2) Well length significantly affects the groundwater drawdown. As the well length increase the groundwater drawdown values decrease and vice versa.
(3) For multi-well systems in mixed aquifer areas where sand drains may be a necessity to connect the aquifers, spacing between sand drains may has a significant impact on the groundwater drawdown values. For the area considered in the current study, it was found that as the spacing between sand drains increases, groundwater drawdown values at excavation center decreases.

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