AMERICAN SOCIETY OF CIVIL ENGINEERS
6th International Engineering and Construction
Conference (IECC'6), Cairo, Egypt, June 28-30, 2010

FINITE DIFFERENCE MODELLING OF GROUNDWATER CONTROL IN URBAN ENVIRONMENT: CASE STUDY

Fathalla m. El-nahhas[1] ,Abdel Menem Sanad[2] , Mahmoud m. Kassem[3]

[1] Professor of Geotechnical Engineering and Foundations,
Ain Shams University, Faculty of Engineering, Cairo, Egypt
E-mail: fnahhas05@yahoo.com
[2] Chairman of Department of Construction Engineering,
Arab Academy for Science & Technology & Maritime Transport,
College of Engineering & Technology, Cairo, Egypt
E-mail: amsanad@hotmail.com
[3] Teaching Assistant, Arab Academy for Science & Technology
& Maritime Transport, College of Engineering & Technology, Cairo, Egypt
E-mail: mahmoudkassem1@hotmail.com

Abstract

Controlling groundwater levels in urban areas using different dewatering processes is considered as a civil engineering challenge in each new project. This is evident due to the current commonly observed gap between design and construction of dewatering systems. Despite the remarkable progress in recent years of groundwater numerical modelling using different techniques, it was agreed that there is an urgent need to use these sophisticated tools for predicting the full scale performance of actual projects in order to build-up confidence in these tools for their use in design of urban projects and/or identify their shortcomings.
This paper presents the results of using a well-known finite difference software package, MODFLOW, for back-analysis of a dewatering system of deep wells that was used to control groundwater level at a site northeast of Cairo, Egypt. Dewatering for the deep excavation of the project was implemented in four stages to make it more feasible and to reduce the effect of groundwater drawdown on the surrounding buildings. The employed dewatering system composed of twenty two deep well and monitored using fifteen piezometers. A pumping test was performed to assess the in-situ values of the coefficient of permeability of the ground mass. Results of the pumping test and groundwater drawdown during the actual dewatering are compared with those of back-analyses utilizing both of the conventional closed-form solutions and numerical analysis using MODFLOW.

Keywords: Groundwater dewatering, deep wells, piezometers, pumping test, back-analysis, numerical modelling, finite difference, MODFLOW.

Introduction

Management and controlling of groundwater levels is a multi-discipline process requiring cooperative efforts from a number of specialists in geotechnical engineering, hydrogeology, hydrology, geochemistry, hydrochemistry..etc. Within urban environments, the geotechnical role becomes crucial in order to assess the implications of changing the groundwater levels and to propose and implement additional safety elements or measures. In many cases, control of groundwater levels is essential to prevent, or at least minimize, the expected detrimental effects on existing adjacent buildings and other structures (El-Nahhas, 2003).

The rise of groundwater levels in urban regions is becoming an alarming problem in recent years. Every new civil engineering project involving construction at elevations below water table most likely requires some measures of groundwater control. On the other hand, shallow foundations and underground floors of old existing buildings, which were constructed above the water table, may suffer of some detrimental attacks of groundwater and possible flooding due to the unexpected rise of water table. The demand for using deep wells has been increasing to lower the water table at the sites of new developments or within existing urban areas (Mossaad et al., 2000).

The design of a dewatering scheme should provide an estimate of the needed pumping capacity and the expected drawdown within and in the vicinity of the area under consideration. Capacity of the dewatering scheme is reflected on several items; such as the number, depth and spacing of the wells and the type and output of the selected submersible pumps. Prediction of the expected drawdown, taking into account the water-soil characteristics and the complex well-to-well interaction, is also considered one of the difficult tasks during the design stages (El-Nahhas et al., 1999).

Extensive reviews of the recommended guidelines of the analysis, design and construction of controlling groundwater are given by Mansur and Kaufman (1962), Somerville (1986) Preene et al. (2000) and Powers (2007). The role of numerical techniques in back-analysis or predicting the performance of dewatering systems have been expanding during last two decades. Several attempts were made to utilize either the finite element or the finite difference methods for such purpose in Egypt; such as: Abdel-Karim (1992), Hassaneen (1998) and Samieh and Mahmoud (2009).

This paper presents the results of using a well-known finite difference software package, MODFLOW, for back-analysis of a dewatering system of deep wells that was used to control groundwater level at a site northeast of Cairo, Egypt. Results of the pumping test and groundwater drawdown during the actual dewatering are compared with those of back-analyses utilizing both of the conventional closed-form solutions and numerical analysis using MODFLOW.

Finite Difference Modelling

The simple form of Laplace's equation, given in Equation 1, represents the potential head "h" of two-dimensional water seepage through a homogeneous anisotropic soil ($k_x \neq k_z$), Verruijt (1970).

$$k_x \frac{\partial^2 h}{\partial x^2} + k_z \frac{\partial^2 h}{\partial z^2} = 0 \qquad (1)$$

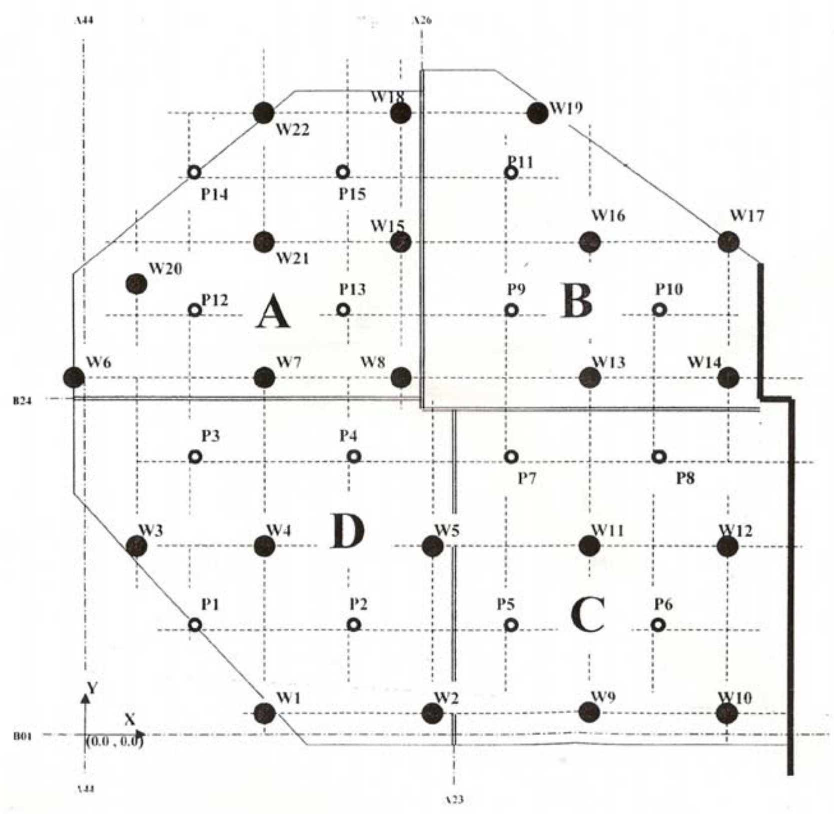
Numerical idealization of this equation in the simple case of isotropic soils can be conducted utilizing the finite difference method at any point "0" away from the boundaries and using a mesh of squares ($\Delta x = \Delta z$), as follows:

$$h_1 + h_2 + h_3 + h_4 - 4h_0 = 0 \qquad (2)$$

Special modifications are made on Equation 2 to represent the hydraulic requirements at the boundary conditions. Hence, the differential Laplace's equation is replaced by a set of simultaneous linear equations representing the actual case with its unique boundary conditions. Well documented and extensively tested software like MODFLOW (U.S. Geological Survey, 2000) utilizes the finite difference method for modelling groundwater flow. This program is also versatile user friendly, having pre- and post-processing that stream line data entry, model construction and analysis and was hence selected for conducting this research.

Case Study

The case study used in this research focuses on the groundwater lowering process during the construction of the foundations and underground elements of a new development in northeast Cairo, Egypt. The proposed reinforced concrete structure of this project consists of a basement on the whole area of the building and up to thirteen upper reinforced concrete floors. The employed dewatering system composed of twenty two deep well, 22-m deep, and monitored using fifteen piezometers (15-m deep), as shown on Figure 1. Full details about this case study are given by Kassem (2010).



Figure(1): Layout of the deep wells and piezometers of the dewatering system

The soil stratigraphy at the site consists of a surface alluvial layer of stiff to very stiff brown silty clay to a depth of about 7.00 m. This layer is underlain by graded to coarse dense to very dense sand with variable contents of fine gravel. The highest reported groundwater level within the upper clay layer was at a depth of about 1.30 m below ground surface. However, the geotechnical investigation indicated that the piezometric head in the lower sand layer may reach the ground surface level. It was recommended that a dewatering system is required to lower the groundwater level to a depth of about 4.75 m below ground surface level.

The operation of lowering groundwater table at this project site was divided into four stages covering four sections of the site area (A, B, C & D) to make it more feasible and to reduce the effect of groundwater drawdown on the surrounding buildings. It was estimated that the daily quantity of water discharged for every stage will be about 11500 m^3 using the 22-m deep wells with average pumping rate of about 60 m^3/h from each well. However, if two stages were operated simultaneously the discharge may reach about 20160 m^3.

Pumping test was performed to evaluate the in-situ values of the coefficient of permeability of the ground mass. Piezometers were used to monitor the changes of groundwater levels and settlement of three nearby buildings was monitor to assess the effect of lowering the groundwater table on them. This research focuses on lowering the groundwater table below the foundation level over Area D of about 4225 m^2. This was the first stage of the dewatering operation of this project utilizing eight deep wells (W1, W2, W3, W4, W5, W6, W7, W8) and focusing monitoring of the changes in groundwater levels at four piezometers (P1, P2, P3, P4) to confirm achieving the target drawdown of 4.75 m.

Back-Analysis of the Case Study

Analysis of Pumping Test

A pumping test is the preferred method for compiling reliable data on hydraulic conductivity, transmisivity, radius of influence, storage coefficient, recharge, capacity of deep wells and other factors that will determine the scope and cost of required dewatering. In the selected case study, the test well (TW) was pumped at an average rate of 65 m^3/h for five hours. The groundwater levels were monitored using four piezometers (P1, P4, P7 and P8). The compiled data of water levels and discharge were observed at small intervals to assure accuracy. The observations are shown in Table 1 and Figure 2.

Back-analysis using of the pumping test results utilizing isotropic closed-form-solutions indicated an average value of the coefficient of permeability "k_{av}" ranging between 2.43×10^{-2} to 3.07×10^{-2} cm/sec. On the other hand, the coefficient of permeability calculated utilizing the gradation data using Hazen formula was 3.97×10^{-2} cm/sec. Another back-analysis of the coefficient of permeability was performed using the MODFLOW program considering both isotropic and anisotropic conditions. For $k_v/k_h=1$, matching of the drawdown values was attained when $k = 4.8\times10^{-2}$ cm/sec (Figure 3). For anisotropic condition, matching was obtained for k_v and k_h of 4.9×10^{-2} and 3.4×10^{-2} cm/sec, respectively, giving a k_v/k_h value of 1.44 as illustrated in Figure 4.

Analysis of Case Study

Extensive trials of numerical modelling and closed-form solutions were conducted for back-analysis of Area D of the case study. The range of used values of the horizontal and vertical of permeability ranged between 1×10^{-2} and 5×10^{-2} cm/sec. Figure 5 compares the results of the analysis using the isotropic and anisotropic conditions. It is evident from these results that the calculated drawdown is significantly affected by the magnitude of the coefficient of vertical permeability.

Table (1): Results of the pumping test

Time (min)	Q (m^3)	TW (0)	P7 (31.24m)	P4 (32.83m)	P1 (71.96m)	P8 (75.44m)
0	26	2.06	2.01	1.95	1.96	1.85
1.0		2.59				
2.0		3.67	2.17			
3.0		3.69		2.16		
4.0		3.71		2.21		
5.0		3.74	2.32			
10.0		3.8	2.36	2.28	2.14	1.99
20.0		3.85	2.45	2.33	2.2	
30.0		3.89	2.45	2.36	2.21	2.04
60.0	91	3.93	2.47	2.39	2.24	2.1
90.0		3.95	2.49	2.43	2.26	2.17
120.0	155	3.96	2.5	2.43	2.27	2.18
150.0		3.97	2.5	2.43	2.27	2.19
180.0	220	3.98	2.5	2.43	2.27	2.19
240.0	289	3.98	2.5	2.43	2.27	2.19
300.0	345	3.98	2.5	2.43	2.27	2.19

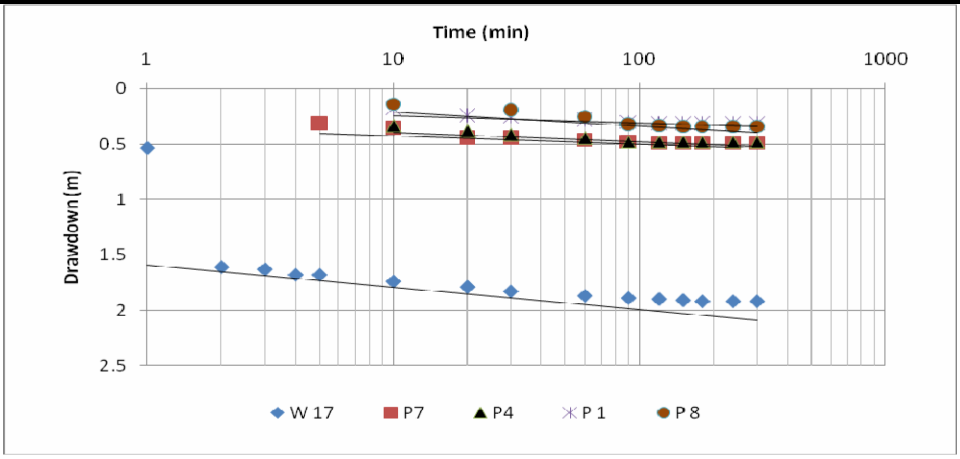


Figure (2) : Drawdown measurements during the pumping test.

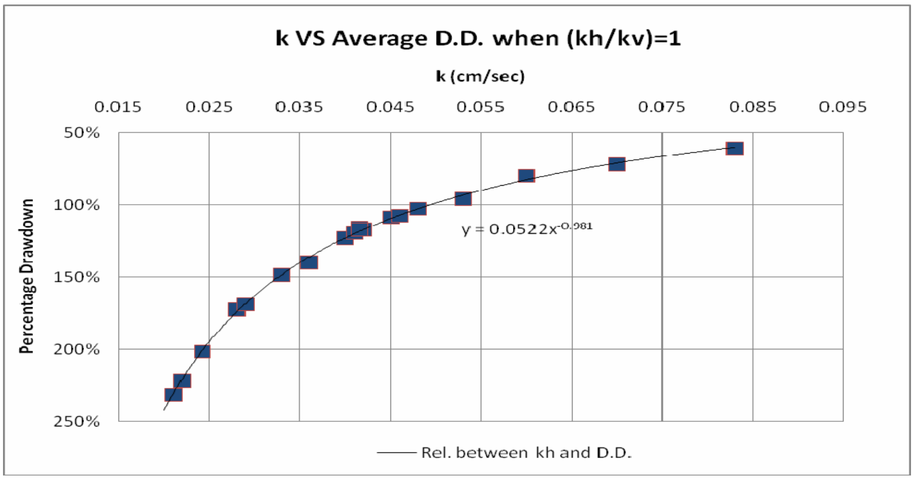
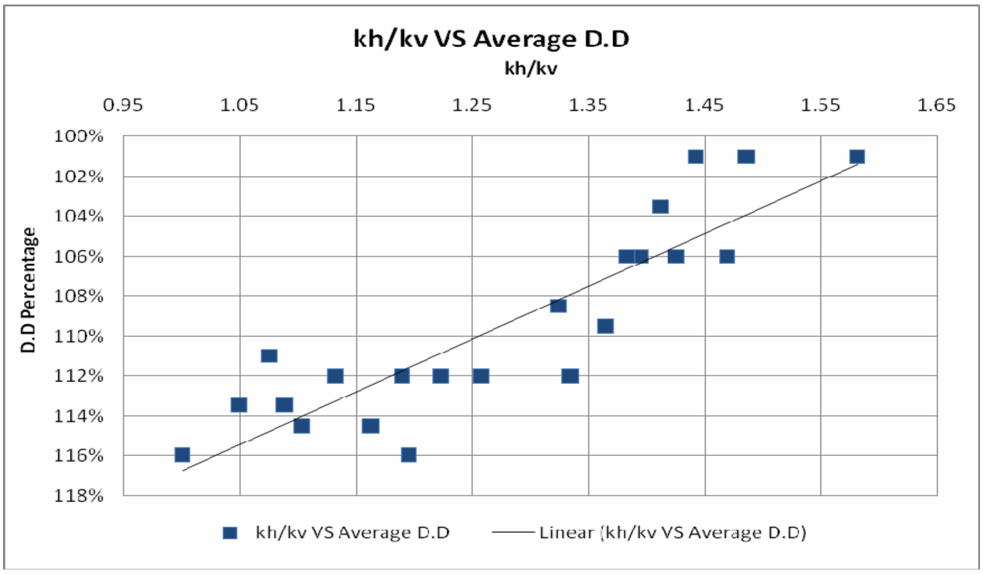
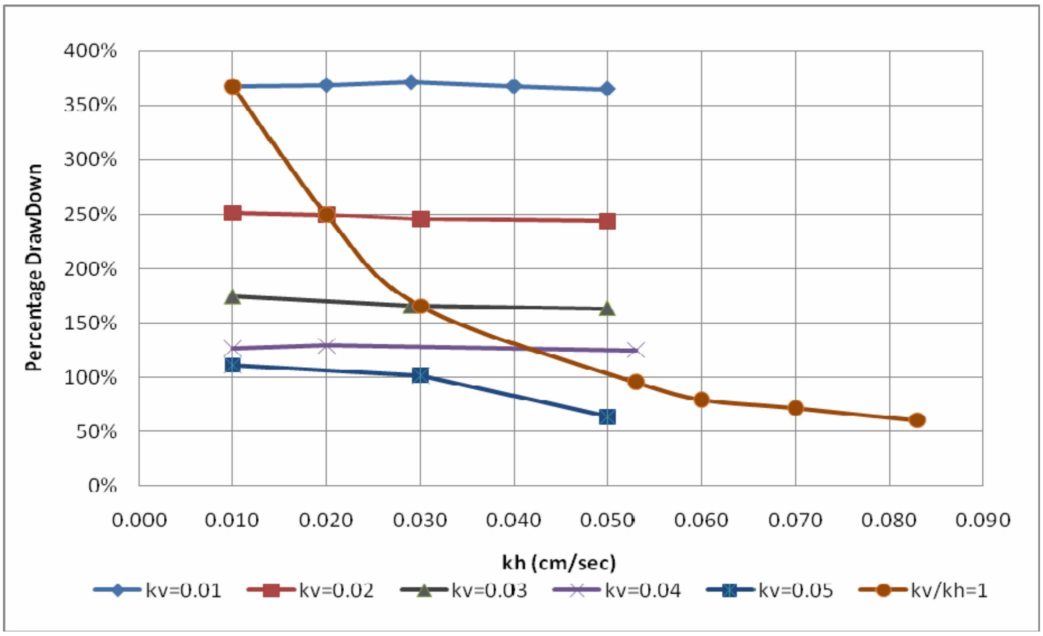


Figure (3): Results of back-analysis of the pumping test for isotropic condition.

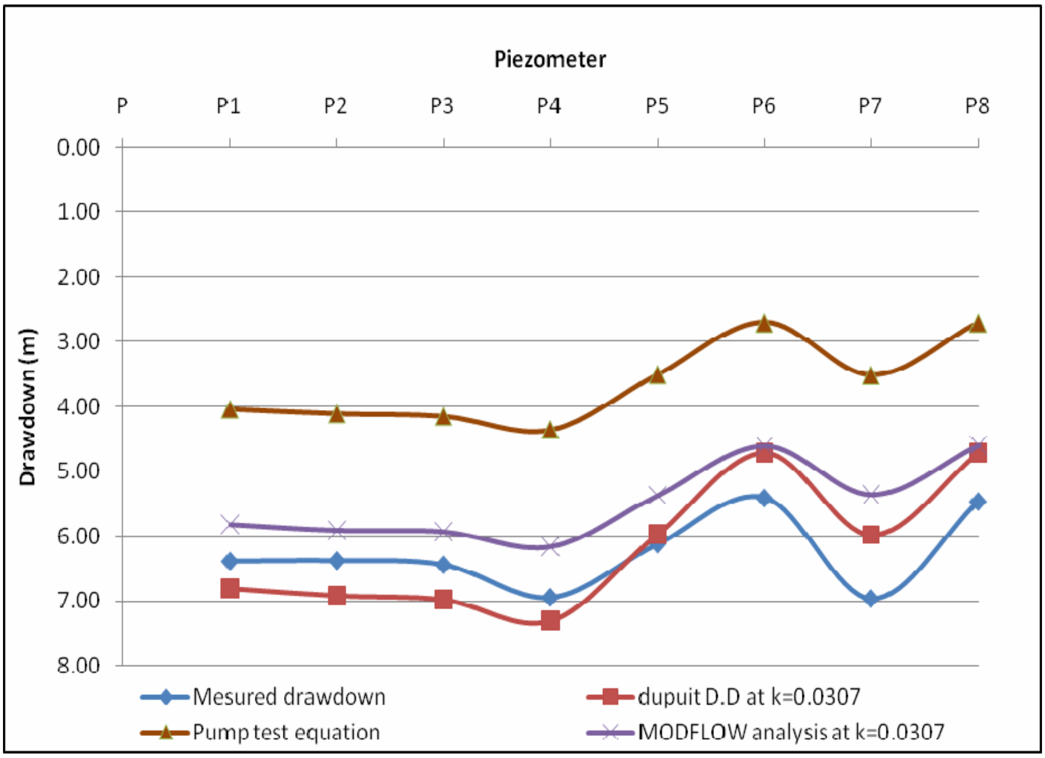


Figure(4) : Results of back-analysis of the pumping test for anisotropic condition.



Figure(5) :Results of back-analysis of the case study using isotropic and anisotropic conditions.

Finally, Figure 6 compares the calculated values of the drawdown using different assumptions with the measured values at some of the piezometers. This comparison confirms that the back-analysis using the MODFLOW model tends to match the field measurements.



Figure(6) :Comparison of the results of back-analysis of the case study with field measurements.

Conclusion

This paper presents the results of back-analysis of a dewatering system that was used to control groundwater level at a site northeast of Cairo, Egypt using the finite difference modelling. Results of the pumping test and groundwater drawdown during the actual dewatering are compared with those of back-analyses utilizing both of the conventional closed-form calculations and numerical analysis using MODFLOW. It is confirmed that the results of back-analysis using the finite difference modelling tend to match the drawdown field measurements.

References

1. Abdel-Karim, A. T. (1992) Analysis of dewatering systems in sandy layers. M. Sc. Thesis, Ain Shams University, Cairo, Egypt.
2. El-Nahhas, F.; Abel-Rahman, M.; and Hassaneen, A. (1999) A case study of lowering groundwater table at Elkobba palace, Cairo. Proc. of the Second Int. Conference on Groundwater Level Control in Urbanized Areas, Mansoura University, Egypt.
3. El-Nahhas, F. (2003) Geotechnical aspects of controlling groundwater levels in urban areas. A Keynote Paper, Proc. of the Tenth Int. Colloquium on Structural and Geotechnical Eng., Ain Shams Univ., Cairo, Vol. 6, KL4.
4. Hassaneen, A. A. (1998) Lowering of groundwater table in urban areas, case study. M. Sc. Thesis, Ain Shams University, Cairo, Egypt.
5. Kassem, M. M. (2010) Geotechnical assessment of dewatering in Cairo, Case Study. M. Sc. Thesis, the Arab Academy for Science and Technology and Maritime

Transport, College of Engineering and Technology, Department of Construction and Building Engineering, Cairo, Egypt (in progress).
6. Mansur, C. I. and Kaufman, R. I. (1962) Dewatering, in Foundation Engineering, G. A. Leonards, ed., NY, McGraw-Hill, pp. 241-350.
7. Mossaad, M.; El-Nahhas, F.; and Al-Sumait, A. (2000) Drawdown-deformation behaviour in a pilot drainage project in Kuwait. Proc. of the Fourth International Geotechnical Conference, Cairo University, Egypt, pp. 625-649.
8. Preene, M.; Roberts, T. O. L.; Powrie, W.; and Dyer, M. R. (2000) Groundwater control-design and practice. Construction Industry Research and Information Association, CIRIA Publication C515.
9. Powers, J. P., Corwin, B. A., Schmall, P. C. and Kaeck, W. E. (2007) Construction dewatering and groundwater control-new methods and applications, 3rd Ed., John Wiley & Sons, New York.
10. Samieh, A. M. and Mahmoud, A. M. H. (2009) Modelling of groundwater lowering in a semiconfined aquifer area. Proc. of the Thirteenth Int. Colloquium on Structural and Geotechnical Eng., Ain Shams Univ., Cairo
11. Somerville, S. H. (1986) Control of groundwater for temporary works. Construction Industry Research and Information Association, CIRIA Publication C113.
12. U.S. Geological Survey (2000) MODFLOW, Modular three-dimensional finite-difference ground-water model.
13. Verruijt, A. (1970) Theory of groundwater flow. Macmillan Civil Engineering Hydraulics Series, Macmillan & Co. Ltd, 190 p.