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Evaluation of complex aquifers with different configurations

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KEYWORDS

Modflow;
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Abstract Three design methods are usually used in the analysis and design of ground water control systems. These methods are: the analysis using equilibrium formulas, the analysis using flow net and the analysis through numerical modeling. Numerical ground water models have proven to be essential when dealing with complex aquifer situations. One of the most known numerical models is ‘‘Modflow’’ which is a three dimensional finite difference model oriented for ground water modeling. The dewatering activities that take place at the Banha power station was utilized in calibrating the performance of the numerical modeling process. A parametric study was carried out with different configurations and boundary conditions. The study covers the performance of sand drains with different depths and spacing. These readings had been compared to ‘‘Modflow’’ results and good agreement between the field data and the analysis results had been observed.

For complex ground water control problems where the assumptions of the conventional equilibrium formulas are not valid, the use of these formulas may lead to serious errors in design. In this condition, the use of 3-D finite difference analysis is essential to obtain reliable results and design for a groundwater control system.

Introduction

Equilibrium formulas have been used for decades in the design of dewatering systems. These formulas were basically developed by Thiem [1] and have been supplemented by many other investigators [2]. The groundwater modeler has to deal with different types of uncertainties, in particular with parameters such as uncertainties [3,4] and conceptualization uncertainties [5], in order to handle conceptualization uncertainty.

The aim of the calculations of a dewatering system using the equilibrium formulas is to determine the required pumping rate and the number of wells needed in order to lower the water level to a desired level. These equilibrium formulas assume an ideal aquifer and in turn, the design using these formulas has several limitations and can only be applied for dewatering problems which are very simplified in their nature [2]. For complex aquifer situations, numerical groundwater models have proven to be a useful and essential tool. These models can deal successfully with the complicities and

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limitations of the design method using the equilibrium formulas [6,7].

The complex aquifer situation includes cases of non-equal constant head boundary, partially penetrating wells, different discharge capacities, soil anisotropy, barrier boundaries, recharge boundaries and multiple aquifer configurations.

This paper, focuses on the use of three dimensional finite difference analysis for the design of deep wells dewatering system and how to model and how to solve by Mod Flow to demonstrate the capability of the three dimensional modeling for dealing with complex aquifer situations. Four case studies have been chosen to compare the result of the mod flow with actual field data. These measurements showed the efficiency and the accuracy of the numerical model.

Problematic problem

Case study (1): Banha power station

Description of the case study

The problem under study is located at the Banha power station. The structure understudy is a deep pump house structure of dimensions (69.45 m × 35.60 m). The ground level is about 0.00, while the foundation level of the structure is at level of −10.00. Figs. 1 and 2 show a section plan of the pump house structure at the foundation level as well as a cross section elevation showing the concrete structure levels.

Soil formation and groundwater level

Detailed site investigation showed that the soil formation along the site is almost constant and includes two main layers. The top layer is impervious clay with a thickness of 11.00 m followed by deep sand aquifer with interlayers of fine gravel to a depth of more than 30 m boreholes.

The groundwater is located at a level of −4.00. Fig. 3 shows the soil formation at the structure location.

Need of dewatering system

Although the excavation level is located at a level of −10.00 inside the top clay layer, a relief system is required to satisfy the safety of the clay layer against piping. Back analysis showed that a drawdown of 6.00 m is required to achieve a safety factor of 1.15.

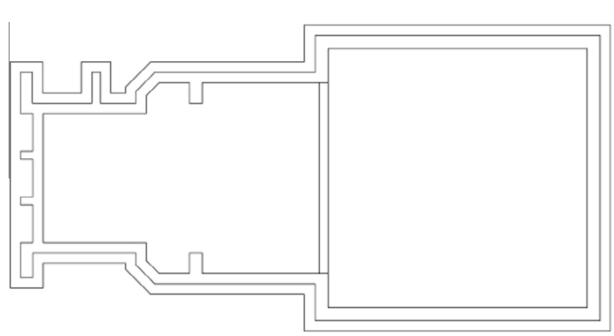

Fig. 1 Section plan for the pump house structure.

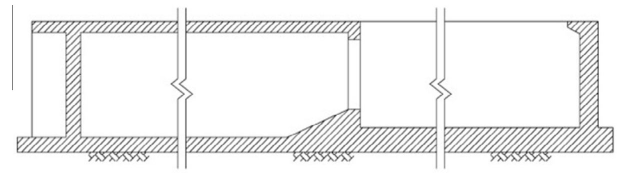

Fig. 2 Section elevation.

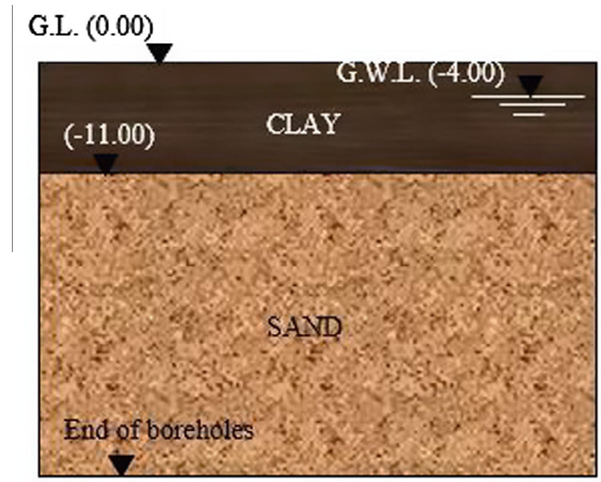

Fig. 3 Soil formation at the structure location.

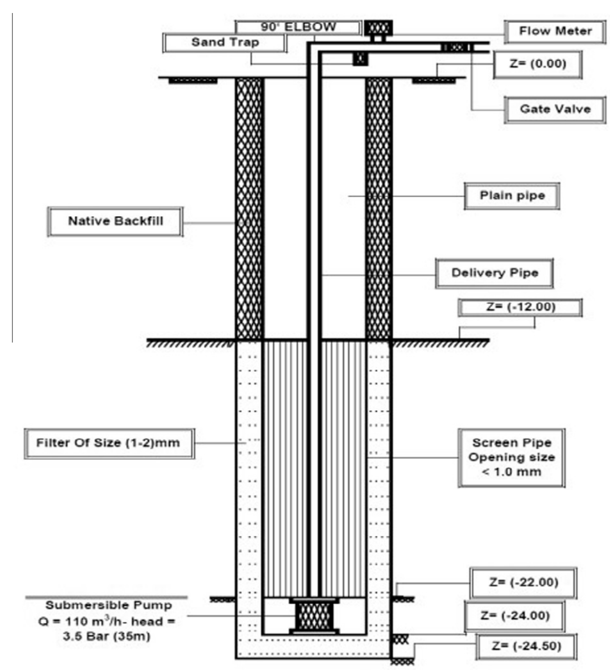

Fig. 4 Typical configuration of dewatering wells.

Wells configuration, distribution and piezometers location

The preliminary design assumed a constant rate of discharge of 110 m^3/h/well. The typical configuration of wells is shown in Fig. 4. The results of preliminary design indicated that the required number of wells was about 16 wells with the distribution shown in Fig. 4. The same figure includes the location of the piezometers around the structure under study (Fig. 5).

Field measurements and revised design parameters

The system was activated and field measurements were taken for the achieved draw down at the installed piezometers shown in Fig. 6. The discharge capacity of each well was also measured through the activated wells. These measurements showed that well discharge capacity is not constant and ranges between 42 m^3/h and 100 m^3/h.

The measured draw down at the selected piezometers was compared with the calculated draw down resulting from the initial design as shown in Fig. 6.

From this figure, it is clear that the value of draw down measured from the site due to the activated wells is less than the initial design draw down values. This is mainly due to the effect of inconsistent well discharge capacities and also the variation in hydraulic parameters. Back calculations were carried out using an average discharge capacity of 83.50 m^3/h. The aim of these calculations is to determine the soil permeability K and the associated radius of influence R which matches the design calculations with the field measurement. The back calculations showed that a permeability value of 2×10^{-2} cm/s and corresponding value of R equal to 270 m will give theoretical draw down values close to the measured values. Fig. 7 shows a comparison between the results of equilibrium analysis using revised soil hydraulic parameters and the field measurements.

From Fig. 7, it can be concluded that there is a good agreement between the theoretical values and the measured ones.

Final revised design using "Modflow"

Introduction. In order to decide on the new required number of wells needed to achieve the target draw down, a numerical model using the finite difference program "Modflow" had been developed. The developed model considered the new revised hydraulic parameters and also the variability of the different discharge capacities noticed for pumps on site.

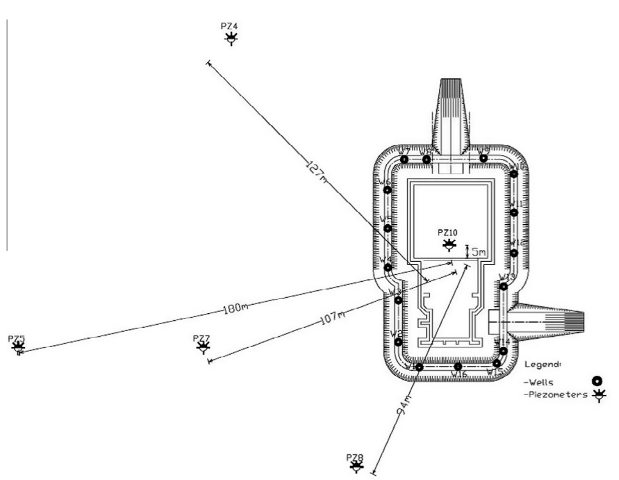

Fig. 5 Arrangement of dewatering wells and monitoring piezometers.

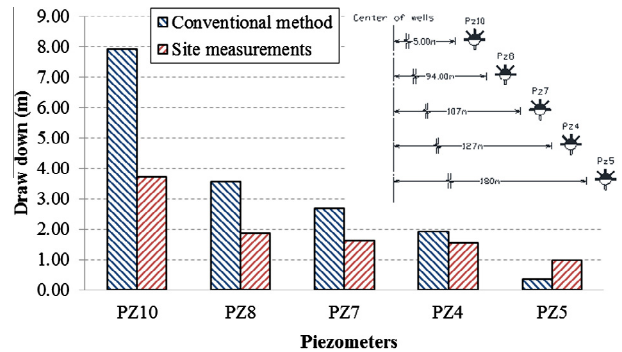

Fig. 6 Comparison between draw down values calculated from the initial design and measured from the field.

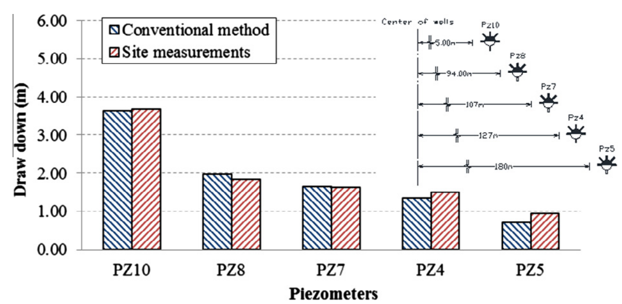

Fig. 7 Comparison between draw down values calculated from the revised design hydraulic parameters and the field measurements.

Model grid arrangement. The model was developed using a rectangular grid arrangement of area 700 m × 550 m with a constant grid spacing of 6 m × 6 m. The grid spacing is also refined around the location of the dewatering wells and the required area to be dewatered with a grid spacing of 1 m by 1 m.

Model boundary conditions. The model incorporates one type of boundary condition which is the average constant head constant head boundary condition to simulate the well radius of influence R. The constant head boundary is assigned at all model sides at equal distance about 270 m measured from the well group center except at the northern side where the distance is taken about 110 m due to the existence of a canal as shown in Fig. 8.

Additional wells. A set of 16 wells as per the initial design were arranged at a typical spacing of about 17.00 m. In addition, a set of 6 additional wells were arranged in between the preliminary wells with a pump discharge capacity of 150 m^3/h/well to increase the efficiency of the suggested well system. The main aim of these wells is to increase the system efficiency in order to achieve the target draw down. The arrangement of the all wells is shown in Fig. 9.

"Modflow" output results. Fig. 10 presents the draw down contour map resulted from the "Modflow" program due to the activation of the initial and new wells considering different discharge capacities of different wells.

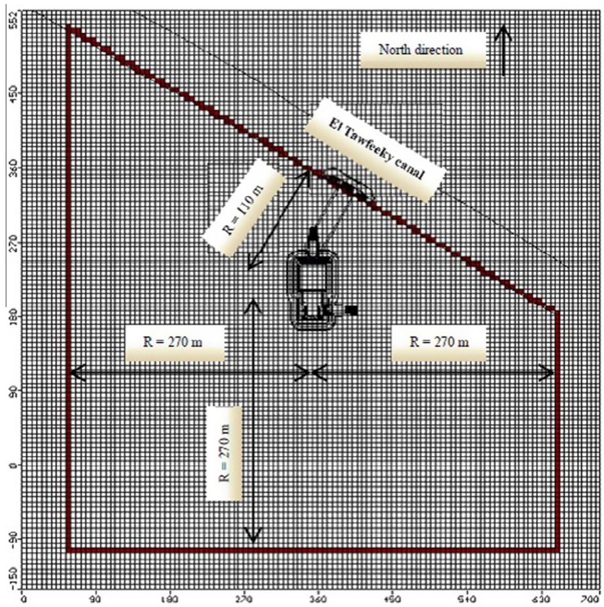

Fig. 8 Model boundary condition from "Modflow".

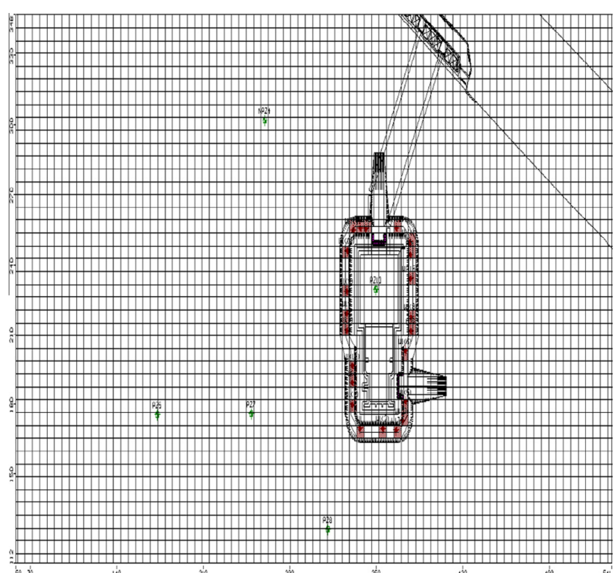

Fig. 9 Initial and additional wells and piezometers location from "Modflow".

Theoretical draw down values versus field measurements

Actual draw down values were recorded through the installed piezometers after activation of the whole system. A comparison had been made between the draw down values resulting from "Modflow" and the values recorded from the site as shown in Fig. 11. This figure shows a good agreement between the enhanced design using "Modflow" and the site measurements.

Case study (2): The effect of using sand drains for multiple aquifer condition

Sand drains are used where a stratified semi-pervious stratum with a low vertical permeability overlies a pervious stratum and the groundwater table has to be dewatered in both strata, the water table in the upper stratum can be dewatered by means of sand drains as shown in Fig. 12.

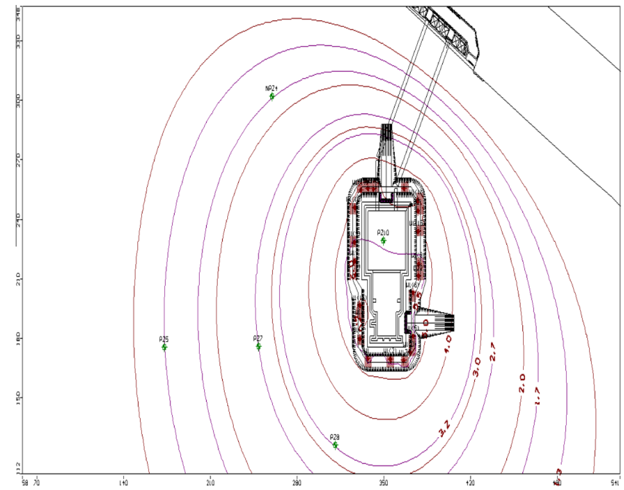

Fig. 10 Draw down contour map resulted from "Modflow".

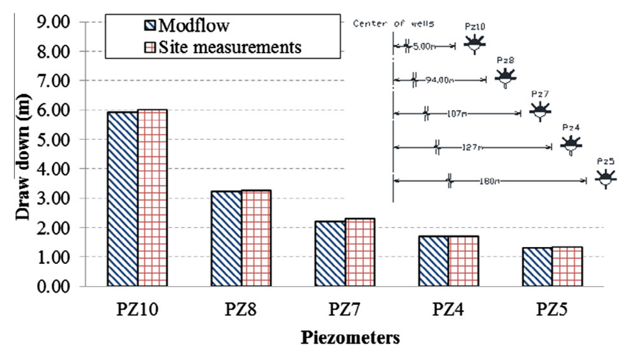

Fig. 11 Comparison between draw down values resulted from the enhanced design using "Modflow" and the measured from field.

Description of the case study

The effect of the sand drains efficiency is considered for a square area of dimensions 40×40 m required to be dewatered about 6.50 m. The soil formation consists of an upper sand layer with a total thickness of about 5.00 m followed by an impervious clay layer of thickness 5.00 m followed by the lower sand aquifer. The dewatering system is composed of eight deep wells arranged around the area and a group of sand drains arranged in between the acting wells as shown in Fig. 13 to connect the two upper and lower aquifers therefore helping in achieving the required draw down.

The sand drain configuration extends from the existing ground level down to 1.00 m below the top of the lower sand layer as shown in Fig. 14.

Well and aquifer configuration

Well information.

- Well radius rw = 152.00 mm solid part length = 10.00 m.

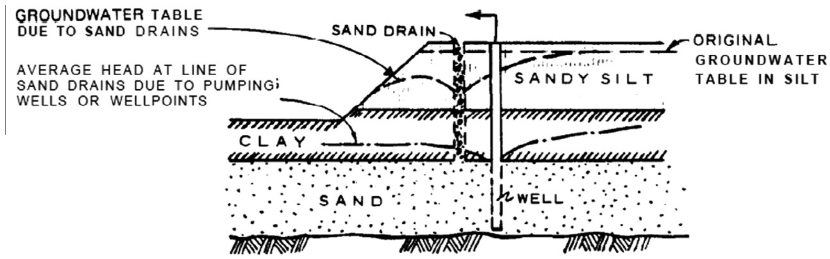

Fig. 12 Sand drains for dewatering a slope (NAVFAC P-418) [8].

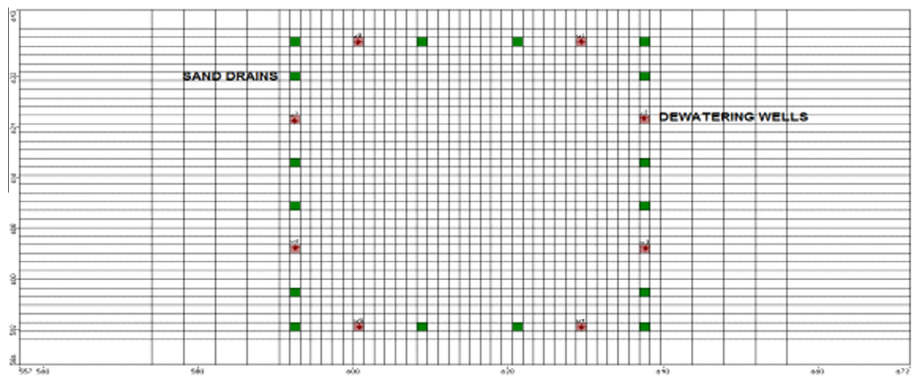

Fig. 13 Sand drains arrangement through Modflow model.

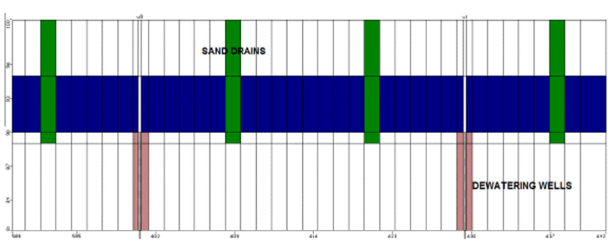

Fig. 14 Typical configuration of sand drain through the different soil formations.

- Screen part length = 10.00 m.
- Well discharge $Q = 90.00\ m^3/h$.
- Well penetration factor $G = 0.282$ (for partially penetrating wells).

Aquifer information.

- Soil permeability $k = 8 \times 10^{-2}$ cm/s (for both the upper and lower sand).
- Aquifer depth $H = 100.00$ m.
- Radius of influence $R = 595$ m.

Modflow output result

Figs. 15 and 16 presents the draw down contours due to the acting wells through the upper and lower sand layers, respectively.

Fig. 15 shows that a draw down value of about 1.85 m was achieved through the upper sand aquifer due to the effect of constructed sand drains between the acting wells which connects the two aquifers together.

Case study (3): The effect of densification of sand drains columns

Sand drains arrangement

In order to increase the efficiency of using the sand drains as a conducting method between the two separate aquifers, a new arrangement with more sand drains point was proposed as shown in Fig. 17. (The number of sand drains would be increased from 16 to 36 wells).

The new proposed sand drains have the same configuration and extends up to 1.00 m below the top level of the lower sand aquifer as shown in Fig. 18.

Modflow output result

Figs. 19 and 20 presents the draw down contours due to the acting wells through the upper and lower sand layers, respectively. Fig. 19 shows that a draw down value of about 2.80 m was achieved through the upper sand aquifer due to the effect of sand drains densification. It is obvious that by increasing the sand drain number almost to the double, the value of draw down increases by about 50%.

Case [4]: Studying the effect of the presence of a cutoff wall

Description of the case study

In this case, a square area of dimensions 10.00 m × 10.00 m is to be dewatered using a single partially penetrating well having a discharge capacity of 25 m^3/h and a screen length of 10.00 m as shown in Figs. 21. The proposed well is located inside a sand aquifer of depth about 30 m having a soil permeability of 4×10^{-2} cm/s followed by an impervious clay layer. An

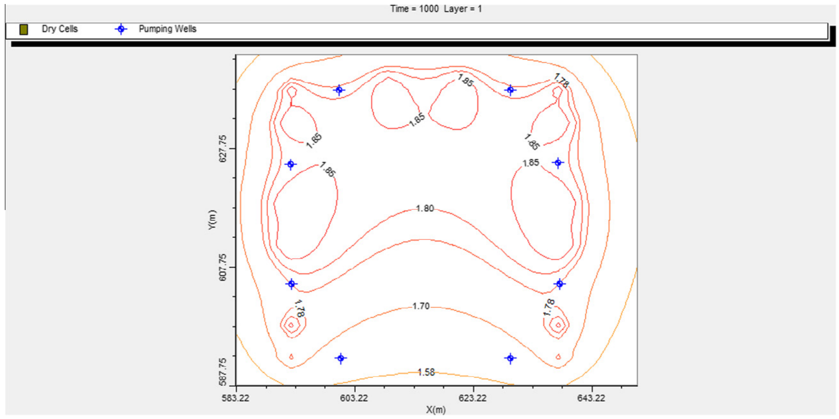

Fig. 15 Modflow draw down contours through the upper sand layer.

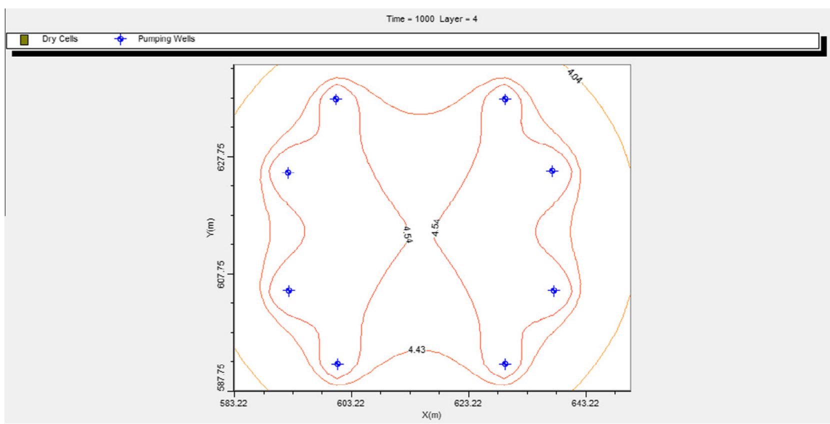

Fig. 16 Modflow draw down contours through the lower sand layer.

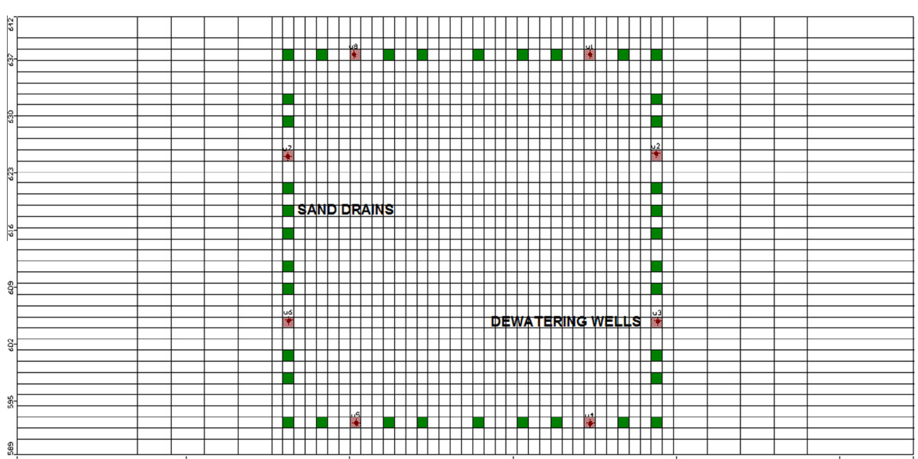

Fig. 17 Sand drains new arrangement.

existing neighbor building was found to be near the area required to be dewatered. In order to eliminate or reduce the effect of the suction well on the existing building, a cut-off wall system is used in front of this building. This cut-off wall is made of concrete of very low permeability (1×10^{-10} cm/s). The analysis shall be done for cutoff walls with a length 20.00 m and 30.00 m length constructed parallel to the existing building.

This study discusses the effect of changing the cut-off wall length on the values of draw down calculated at the different points shown in Fig. 21. Also the efficiency of using this system is monitored through three piezometers (A, B and C) in front

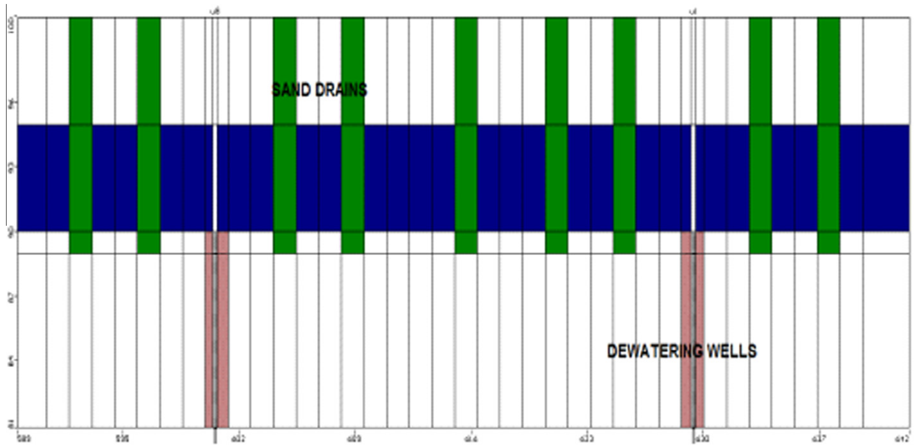

Fig. 18 Typical configuration of sand drain through the different soil formations.

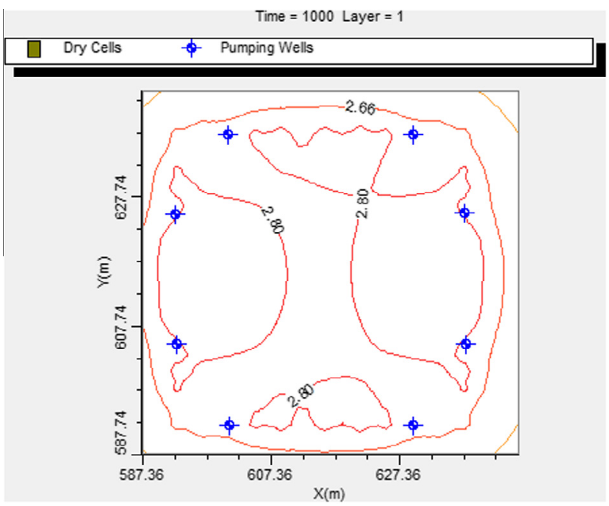

Fig. 19 Modflow draw down contours through the upper sand layer.

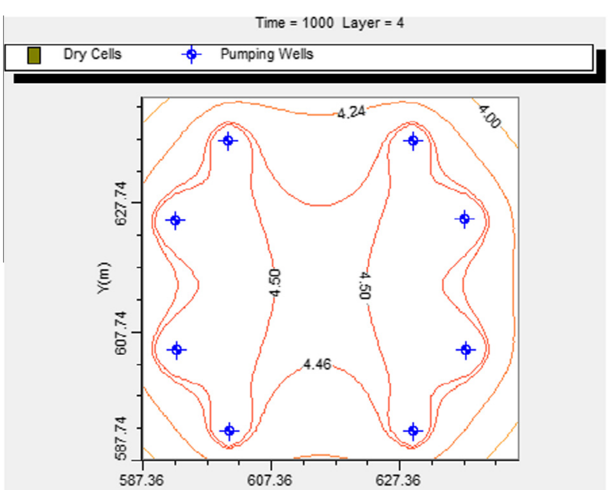

Fig. 20 Modflow draw down contours through the lower sand layer.

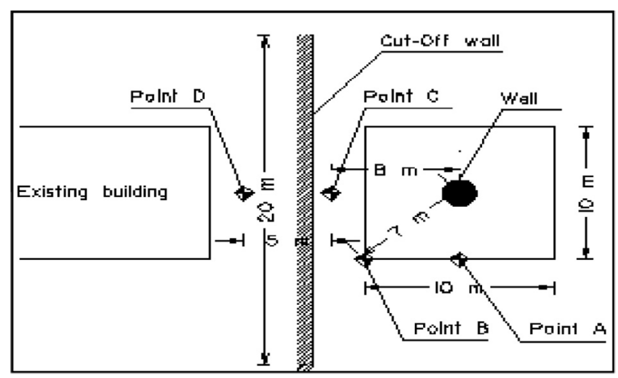

Fig. 21 Plan for the area understudy showing the location of piezometers and the proposed cut-off wall.

of the cut-off wall and one piezometer (D) behind the cut-off wall in order to verify the effect of the wall and also the effect of changing its depth.

The model development using Modflow

Fig. 22 shows the model grid dimensions. The model grid spacing is 10 m by 10 m and expands to 300 m by 300 m. The grid spacing is also refined around the location of the dewatering well and the required area to be dewatered with a grid spacing of 1 m by 1 m.

The model incorporates one type of boundary condition which is the constant head boundary condition to simulate the well radius of influence which is located at the model edges at a distance 150 m from the well. Fig. 23 shows a plan for the pumping well location as well as the selected piezometers and the location of the cutoff wall.

Modflow output results

Fig. 24 show the draw down contour maps of the above mentioned problem and the effect of using a cut-off wall of a depth 20 m.

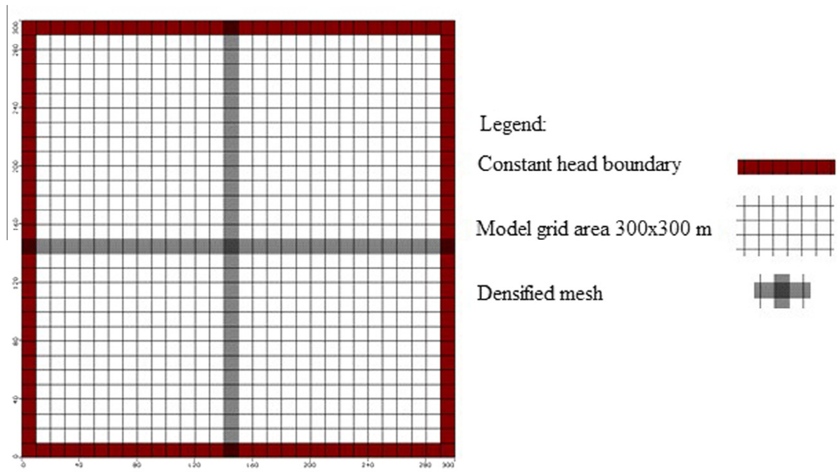

Fig. 22 Modflow model grid and model boundary.

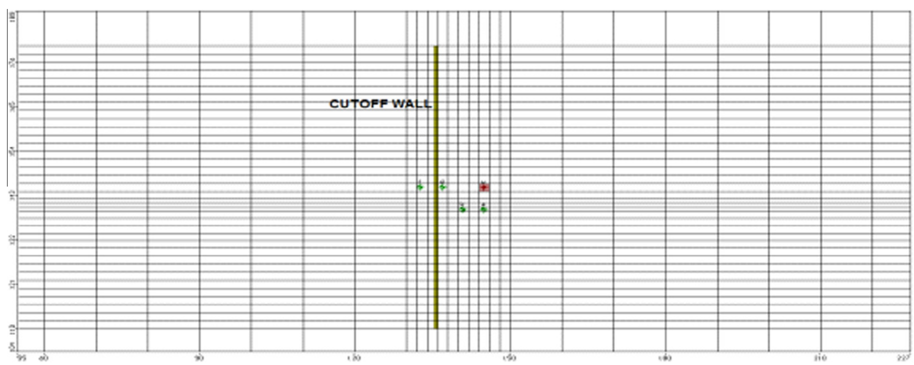

Fig. 23 Plan showing the dewatering, piezometers and cut-off wall location.

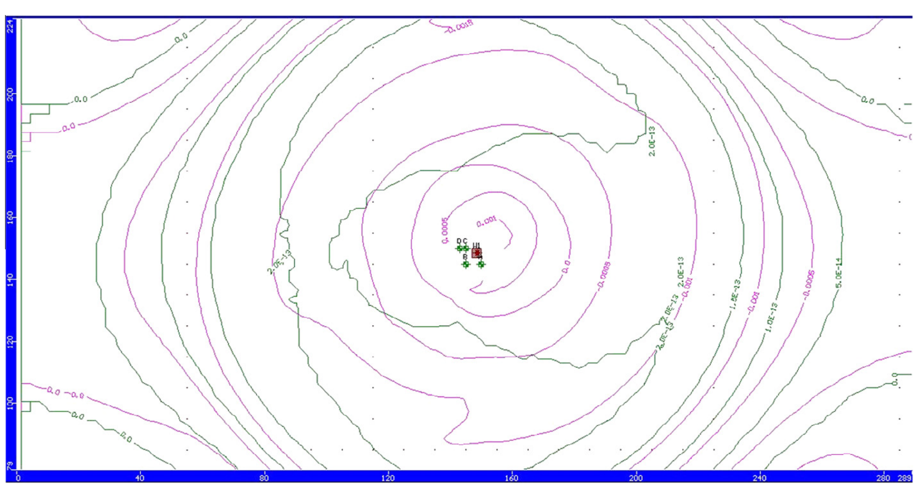

Fig. 24 Draw down contour under the effect of no cut-off wall of length $L = 20$ m.

Fig. 25 show the draw down contour maps of the above mentioned problem and the effect of using a cut-off wall of a depth of 20 m.

Fig. 26 show the draw down contour maps of the above mentioned problem and the effect of using a cut-off wall of a depth of 30 m.

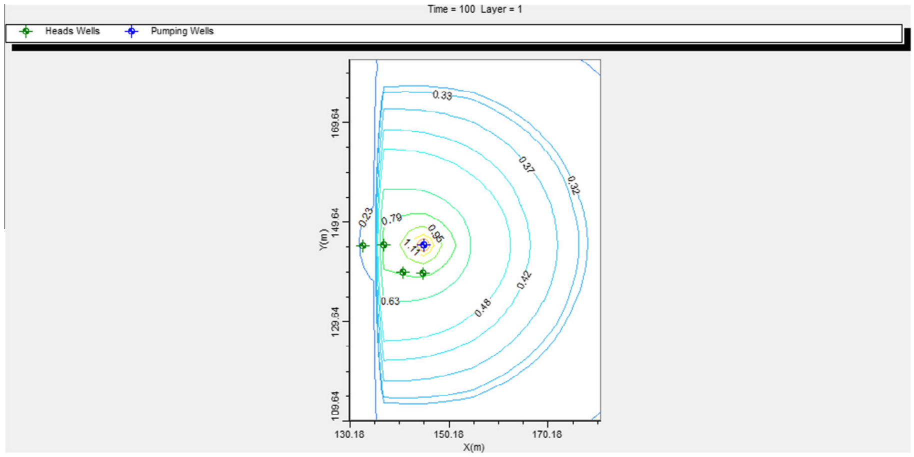

Fig. 25 Draw down contour under the effect of using a cut-off wall of length $L = 20$ m.

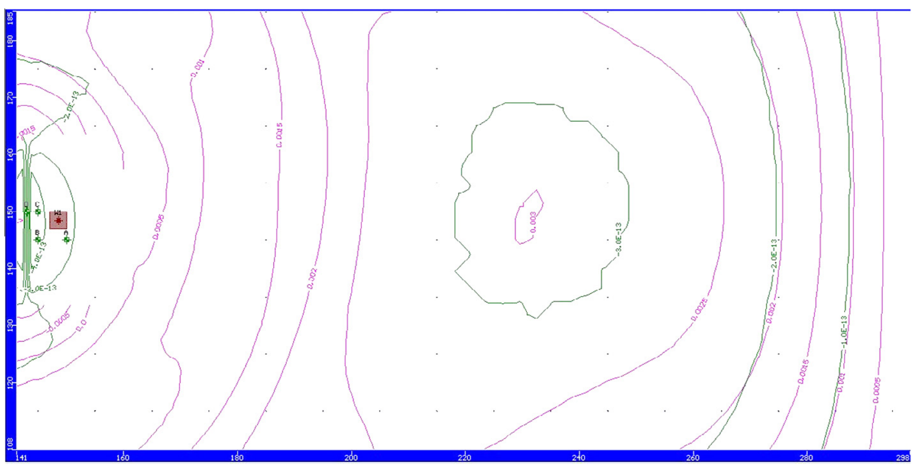

Fig. 26 Draw down contour under the effect of using a cut-off wall of length $L = 80$ m.

Conclusions

This paper is focusing on the use of three dimensional finite difference analysis for the design of deep wells dewatering system. The work done through this paper had been carried out using the computer software ''Modflow'' which is widely used for the simulation of complex groundwater flow problems.

For complex ground water control problems, where the assumptions of the conventional equilibrium formulas are not valid, the use of these formulas may lead to serious errors in design [5]. For this condition, the use of 3-D finite difference analysis is essential to have reliable results and design for ground water control systems.

The complex ground water control problems where the use of 3-D finite difference is mandatory includes soil anisotropy, barrier conditions (partial cut-off walls), recharge boundaries and multiple aquifer conditions.

Three dimensional finite differences for ground water modeling has proved to be the best approach for dealing with complex aquifer conditions which includes one or more of the restrictions mentioned before [9,10]).

A case study which is a relief deep well used for the Banha power station – Egypt had been used to compare the results of the finite difference analysis versus the actual field performance. Different factors which effect on the behavior of the dewatering system had been considered in the finite difference analysis. These conditions include partially penetrating wells, different discharge capacities of wells, and different constant hydraulic heads around the dewatering area. The hydraulic parameters had been back-figured from the actual reading recorded during the activation of the well group. The results of the ''Modflow'' model had been compared to the actual field data recorded after activation of the full dewatering system.

Based on the results of the analysis presented in this paper, the following conclusions can be advanced:

- Three dimensional finite difference analyses is an effective tool for study the behavior of ground water control systems.
- The equilibrium conventional formula for confined aquifer assumes ideal aquifer conditions can be used for simple ground water control problems where the assumptions of these formulas are applied.
- For complex ground water control problems where the assumptions of the conventional equilibrium formulas are not valid, the use of these formulas may lead to serious errors in design. For this condition, the use of 3-D finite difference analysis is essential to have a reliable results and design of the groundwater control system.

- The combination between the field measurements and the constructed 3D model help in raising the efficiency of the system and increase the credibility of the model.
- Effect of incorporating additional inner sand drains results in more homogenity in the draw down compared with increasing the number of the sand drains.
- Increasing the depth of the cutoff result in the impervious affect the reduction in the seepage pressure in the adjacent building by 99%.
- Field monitoring of dewatering systems using observation wells (piezometers) and also measuring well discharge capacities is essential to evaluate the efficiency of the dewatering system.
- Variable discharge of dewatering wells (due to change of the pump capacity and efficiency) must be considered in the design of the dewatering system. Using average discharge for design purposes may be adequate for preliminary design. However, actual discharge of each pump must be considered in the final design verification. This can be considered easily throughout the 3-D finite difference models.
- Results of numerical model using 3-D finite difference analysis showed good agreement with field readings.

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