The 3D Simulations of Groundwater Flow during the Large-scale Pumping Test of Group Wells in Taipei Basin

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Abstract: This study applies the 3D finite-difference groundwater flow model MODFLOW to establish the regional hydrogeological conceptual model of Taipei Basin, which is based on the numerous and widespread data of geological exploration and groundwater measurement. The conceptual model is used to simulate the regional groundwater flow during the large-scale pumping test of group wells for the deep excavations of Taipei MRT underground stations. Simultaneously, the monitoring data of groundwater pressure drawdown during the pumping test are recorded to analyze and evaluate the near-field hydraulic parameters of the deep confined aquifer in Taipei Basin. Finally, the effects of boundaries, recharges and vertical leakages on the simulations of groundwater flow are discussed.

Keywords: pumping test, group wells, conceptual model, Taipei Basin, MODFLOW

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1. Introduction

Recently, the large-scale deep excavations for underground stations of Taipei MRT route networks are continuously under construction. In Taipei Basin, the shallower sedimentary formations, named as Shongshan formation, are soft, weak, and with a high groundwater table. Below Shongshan formation, there is a high-pressure confined aquifer composed mostly of gravel, named as Jingmei formation. Therefore, once the construction of deep excavations approaches the confined aquifer, the high pressure within the confined aquifer must be appropriately reduced to conform to the related technical codes for the deep excavations. The deep-well pumping technique is an effective and a familiar method to reduce the pressure of the deep confined aquifer. In order to ensure the safeties of the site and the adjacent buildings and to avoid an accident due to the long-term pumping, the large-scale pumping test are carried out in advance. The monitoring data of piezometers during the pumping test are used to understand the long-term effects on the nearby environment and to obtain the aquifer characteristics of the gravelly confined aquifer.

In the past, there have been numerous studies in several topics relative to Taipei Basin, such as the studies of geological characteristics and structural faults, the discussions of groundwater resources, the settlement problems resulted from pumping groundwater, and so on. However, few studies have been done on the combination of geology and groundwater in Taipei Basin.

This paper attempts to combine the conditions of geography, stratigraphy, geology and groundwater for Taipei Basin to establish a 3D regional hydrogeological conceptual model. The conceptual model is built up by MODFLOW and the related packages, attached to a commercial numerical program GMS (GMS is a professional groundwater modeling software for simulating 3D groundwater flow and transport. The kernel package of GMS is MODFLOW, which has been established by U.S. Geological Survey since 1983 and its validity has been verified by numerous researchers of many countries. Besides,). This paper presents the regional hydrogeological conceptual model of Taipei Basin and successfully predict the pressure drawdown during the large-scale pumping test of group wells in the Taipei MRT project.

2. Description of Taipei Basin

2.1 Geography

Taipei Basin, located in the northern Taiwan, covers approximately an area of 243 km^2 under the elevation of 20m. The northern part of Taipei Basin adjoins the Datun volcanoes area; the western part neighbors with the Linkou tableland; the eastern and southern parts are around the hills; the middle of basin is passed by Danshui River, which has three main branches (i.e. Keelung River, Shindian Stream and Dahan Stream) and finally flows northward into the Taiwan Strait. All of the above are illustrated in Fig. 1.

Fig. 1 The location of Taipei Basin

2.2 Stratigraphy

Taipei Basin is a sedimentary basin, which has developed from repeatedly alternating between land and lake for the past four hundred thousand years. Therefore, there are several layers of sediments of Quaternary above the basement of Miocene. The sources of sediments include the soft clays from Keelung River, the gravels from Shindian Stream, and the sands from Dahan Stream, respectively. Tan Keinosuke (1939) first named the alternation of sands and clays as Shongshan Formation; named the formation composed of red soils and gravels below Shongshan Formation as Linkou Formation in Taipei Basin. According to the data of boreholes, Wu (1965) proposed that there is a thickness of 200m formation composed of gravels, sands and clays with different characteristics from Linkou Formation, below Shongshan Formation, and named it as Shinchuang Formation to replace Linkou Formation. Wang (1978) found that an independent gravelly formation exists between Shongshan Formation and Shinchuang Formation, and named it as Jingmei Formation. Hereafter, the three-layer nomenclature (i.e. Shongshan, Jingmei and Shinchuang Formations, from shallow to deep) is most commonly used by engineering. The typical geological profiles of Taipei Basin are shown in Fig. 2 (Central Geological Survey, Taiwan, 1999).

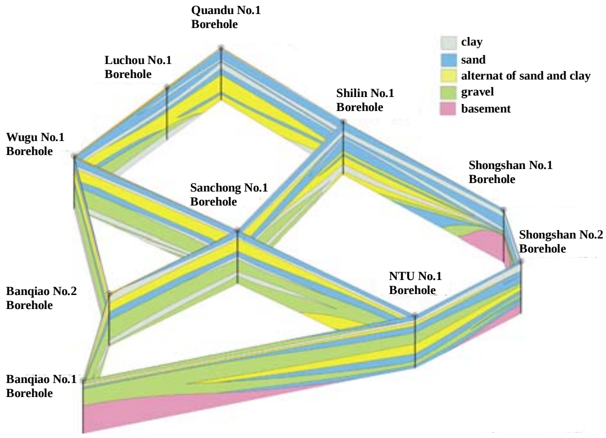

Fig. 2 The geological cross sections of Taipei Basin

2.3 Geological Structure

In a view of geological structures, there are mainly several structural faults around the Taipei Basin including the northwestern Shinchuang Fault, the western Shanjiao Fault, the southeastern Taipei Fault, and the Qianjiao Fault in the middle part. It deserves to be mentioned that Qianjiao and Taipei Faults are the subduction below the sediments of Taipei Basin, and both Shinchuang Fault and Shanjiao Fault divide the sediments of Taipei Basin from Linkou Tableland (see Fig. 3).

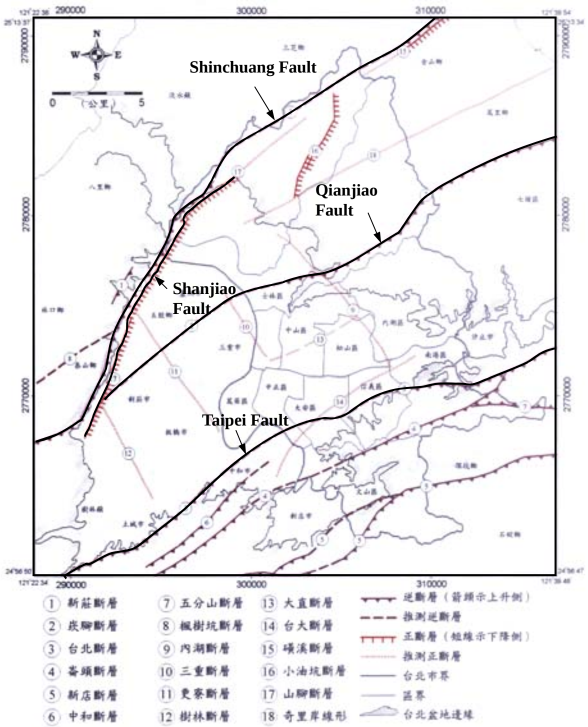

Fig. 3 The structural faults of Taipei Basin

2.4 Groundwater

The primary zones of groundwater recharge of Taipei Basin locate at the midstreams of Shindian Stream and Dahan Stream. In the eastern part of Taipei Basin, the river water and rainfall flow into the aquifers by the infiltration but hydraulic gradient of Keelung River is small and the infiltration is impeded by existing aquitards so that the vertical recharge is fewer over there. The secondary sources of groundwater recharge of Taipei Basin are the lateral flows from the outside of the basin through the deep aquifers such as mountains, hills, and tablelands (Jia et al., 1999). Environmental & Infrastructural Technologies, Inc. (2000) has estimated the groundwater recharge of Taipei Basin by using the in-situ tests and proposed the annual vertical recharge are 0.66, 0.50 and 0.44 hundred million tons for the peak run-off year, the mean run-off year and the minimum run-off year, respectively. Lee et al. (2002) proposed the total groundwater recharge of Taipei Basin based on the baseflow analysis is about 1.2 hundred million tons. Furthermore, Water Resources Agency of the Ministry of Economic Affairs of Taiwan installed more than 20 observation wells in Taipei Basin to monitor the groundwater tables over the years. The positions of these installed wells and the distribution of the monitoring groundwater tables are shown in Fig. 4. according to the monitoring data provided by Water Resources Agency (2003).

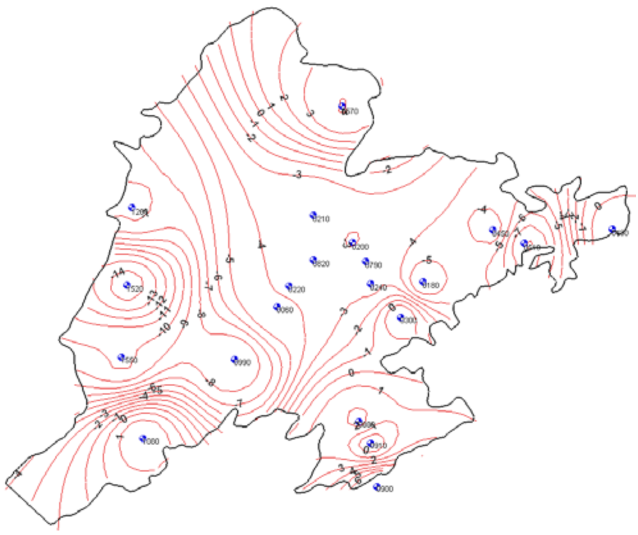

Fig. 4 The positions of observation wells and the distribution of groundwater table in Taipei Basin

3. Hydrogeological Conceptual Model

The objective of hydrogeological conceptual model is to simplify the real physical environment to a ideal model by the processes of dividing and delaminating for aquifers and the balancing water budget which are based on the viewpoints of hydrogeology. The conceptual model consists of several hydrogeological units. Inside the conceptual model, the groundwater flow depends on the principle of water budget, and the flow field can be obtained by solving the government equation of groundwater flow with the initial conditions, the boundary conditions and the applied hydraulic stresses.

3.1 Model Design

This study builds up the 3D regional hydrogeological conceptual model according to the data of geography, stratigraphy, geology and groundwater for Taipei Basin. The conceptual model consists of two kinds of hydrogeological units: the upper unit is the unconfined aquifer (Shongshan Formation) and the lower one is the confined aquifer (Jingmei Formation). Because the thickness of sediments in the basin, especially the gravelly aquifer, are apparently various, the traditional 2D or 3D analyses without considering the variation on the uniformity will be inappropriate. The proposed conceptual model overcomes the limitations of the traditional numerical simulations and considers both the change in terrain and the distribution of thickness for each hydrogeological unit in space so that it could obtain the more correct and more accurate results of analysis.

The hydrogeological conceptual model is set up based on the DTM data stored in the GIS Database Management Platform and based on the boreholes database belongs to the Geotechnical Engineering Network Platform (both the platforms were developed by Sinotech Engineering Consultants, Inc.) and refers to the related studies of stratigraphy of Taipei Basin proposed by Shie et al. (1999) (as shown in Fig. 5). The processes of building conceptual model are described as follows.

First, we build up the original 3D numerical model grid for Taipei Basin conceptual model. The 3D grid has 50×50×8 cells. Each cell represents 500m×500m in area and 20m in depth. The 3D grid is divided into 8 layers, in which the 1st to 6th layers are regarded as the upper unconfined aquifer (Shongshan Formation) and the 7th to 8th layers are regarded as the lower confined aquifer (Jingmei Formation). Then, we use the function of interpolation, which is based on the principle of linear interpolation, to modify the geometric relationship in space for each layer according to the DTM data and boreholes data.

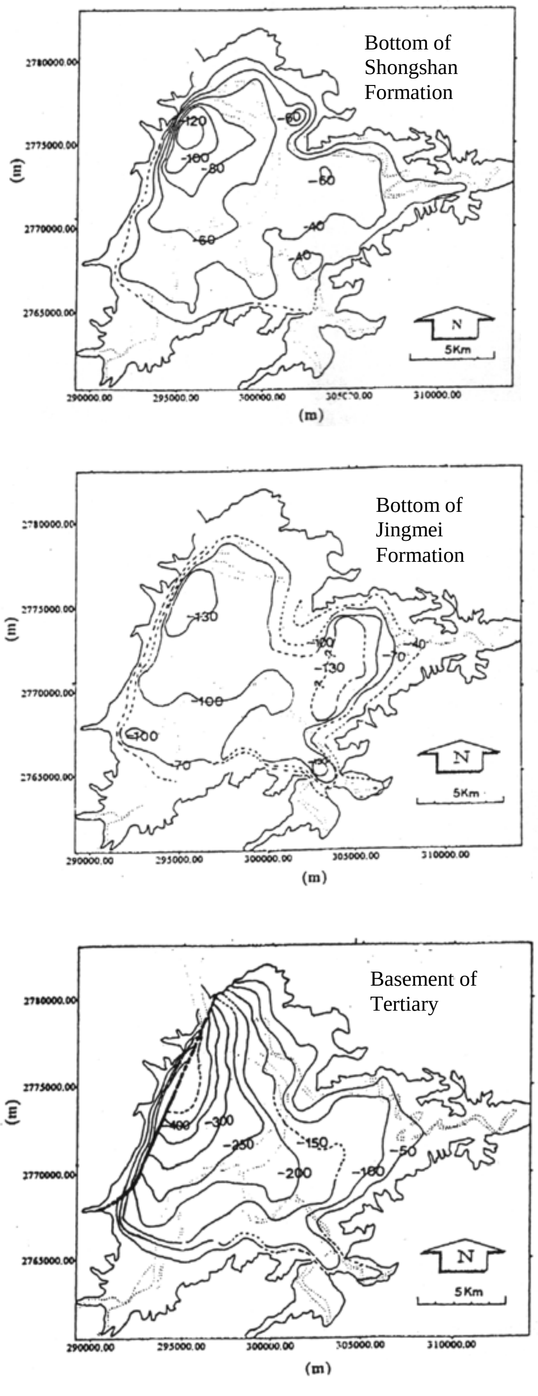

Fig. 5 The distribution of the sediments of Taipei Basin (Shie et al., 1999)

Fig. 6 shows the conceptual model of Taipei Basin which has been modified by interpolating layers. Fig. 7 displays the cross sections of the conceptual model of Taipei Basin. (Note: we have magnified the z-coordinate in Fig. 6 and Fig. 7 so that the vertical variation in the data is more apparent). Finally, we refer to the results of research proposed by Yang (1972) and Tsao et al. (1984) to assign the hydraulic characteristics of confined aquifer by separate zones. The assigned values of hydraulic characteristics of the confined aquifer for each zone are listed in Table 1. Fig. 8 shows the arrangement of all zones. The hydraulic conductivity (K) and the storage coefficient (S) are given respectively the initial values K=0.1 (m/day), proposed by Ou et al. (1983), and S=0.1, suggested by Shao (1995).

This paper applies the MODFLOW and the related packages supported by GMS to carry out the previous processes of building model. GMS is a professional groundwater modeling software for simulating 3D groundwater flow and transport. The primary kernel package of GMS is the MODFLOW, the modular finite-difference groundwater flow model, which has been established by U.S. Geological Survey (USGS) since 1983 and its correctness has been generally verified for last 20 years. The LPF (Layer Property Flow) finite-different method is adopted to solve the government equation of groundwater flow with the PCG2 (Preconditioned Conjugate-Gradient II) numerical method, which has the advantage of the better stability and the faster convergence.

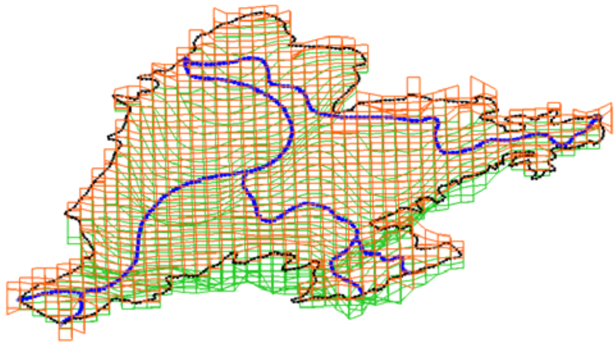

Fig. 6 The 3D hydrogeological conceptual model of Taipei Basin

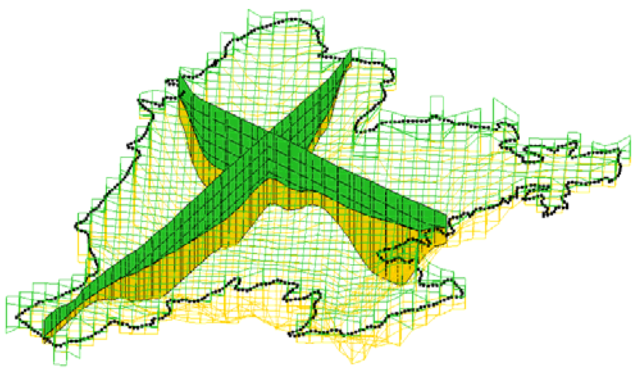

Fig. 7 The hydrogeological cross sections of Taipei Basin

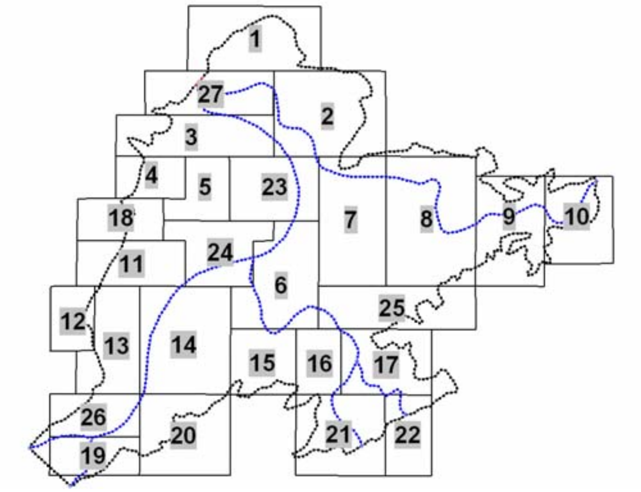

Fig. 8 The hydraulic characteristics zones of Taipei Basin

Table. 1 The hydraulic parameters of the confined aquifer of Taipei Basin

Zone No.	Transmissibility (T) (m^2/day)	Storativity S
1	220	0.001
2	400	0.001
3	800	0.001
4	1500	0.001
5	150	0.001
6	1200	0.002
7	2800	0.002
8	250	0.002
9	1000	0.002
10	450	0.002
11	800	0.001
12	1750	0.001
13	700	0.015
14	200	0.005
15	400	0.001
16	400	0.001
17	400	0.008
18	1000	0.001
19	200	0.015
20	200	0.007
21	150	0.015
22	150	0.015
23	2800	0.001
24	4500	0.001
25	2200	0.005
26	500	0.010
27	270	0.001

3.2 Groundwater Recharge

The results of research proposed by Lee et al. (2002) are directly applied to assign the input value of groundwater recharge for the conceptual model. The input value of the annual groundwater recharge is approximately 1.2 hundred million tons, which is obtained from the baseflow analysis by Lee et al. (2002). The baseflow analysis is a technique, suggested by USGS, to separate baseflow from the river discharge with the hydrograph. According to the principle of water budget, the baseflow is regarded as the groundwater recharge. Fig. 9 and Fig. 10 present the concept of baseflow analysis described by Lee et al. (2002).

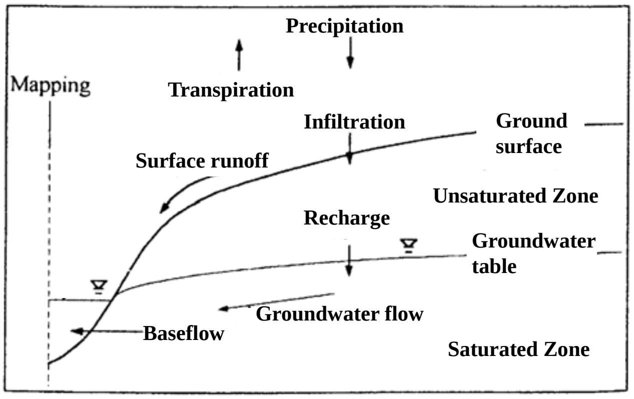

Fig. 9 The principle of water budget (Lee et al., 2002)

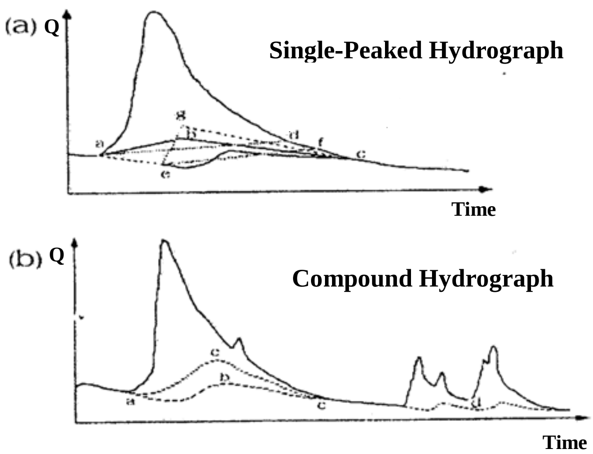

Fig. 10 The principle of baseflow (Lee et al., 2002)

3.3 Boundary and Initial Conditions

Besides the northwestern Shinchuang Fault, the western Shanjiao Fault and the northern estuary of Danshui River for Taipei Basin, there are no other obvious natural boundaries available. Therefore, the boundary conditions of Taipei Basin conceptual model are specified as follows: (1) the estuary of Danshui River regarded as the constant-head boundary, (2) the eastern and southern hills, the northern volcano area, and the western tableland regarded as the variable-head mountain boundaries, and (3) the midstreams of Shindian Stream and Dahan Stream, and Keelung River regarded as the watershed variable-head boundaries. All boundary conditions are shown in Fig. 11.

Fig. 12 displays the initial groundwater table (according to the monitoring data of observation wells in 2003) regarded as the initial conditions of the conceptual model.

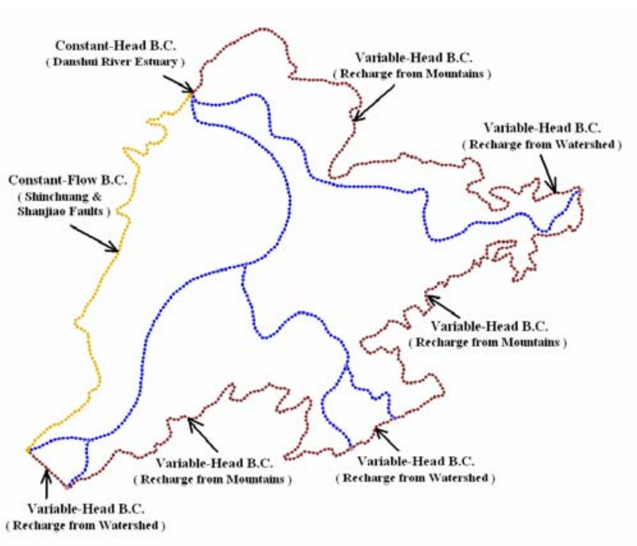

Fig. 11 The boundary conditions of the hydrogeological conceptual model of Taipei Basin

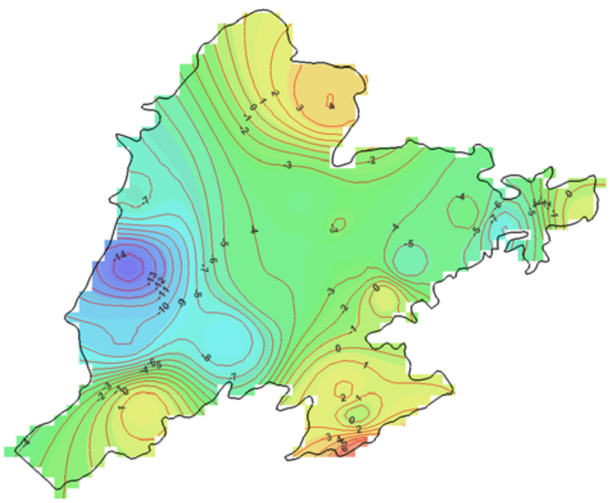

Fig. 12 The distribution of groundwater of Taipei Basin (Water Resources Agency, MOEA, 2003)

3.4 Model Calibration

The model calibration belongs to the inverse problem, i.e. to estimate the hydraulic parameters or the in-situ hydraulic stresses (such as the pumping rate) of the conceptual model by measuring the head or the discharge in the field. In Taipei Basin, huge amount of groundwater was pumping to supply the requirements of the industry, the agriculture, and the people's livelihood in the past. It caused that the maximum drawdown of groundwater table in Taipei Basin reached to 45m. The government has begun to limit people to pumping groundwater since 1968; therefore, the groundwater table in Taipei Basin has gradually raised. This study simulates the present groundwater table in Taipei Basin by the imaginary pumping or injecting wells. The results of simulation are regarded as the present steady flow field. We apply the MODFLOW 2000 PES package to perform the automated parameter estimation to calibrate the pumping (or injecting) rate for each imaginary well according to the monitoring groundwater table in 2003. The results of model calibration are presented in Fig. 13. The components of a calibration target are also illustrated in Fig. 13. The center of the target corresponds to the observed value. The top of the target corresponds to the observed value plus the interval (i.e. the allowable error) and the bottom corresponds to the observed value minus the interval. The length of bar represents the error. If the bar lies entirely within the target, the color bar is drawn in green. In this case, the allowable error is assign to be ±0.5m and the confidence in the error estimation is 95%. It shows that the conceptual model of Taipei Basin we built has a good validity and a great accuracy.

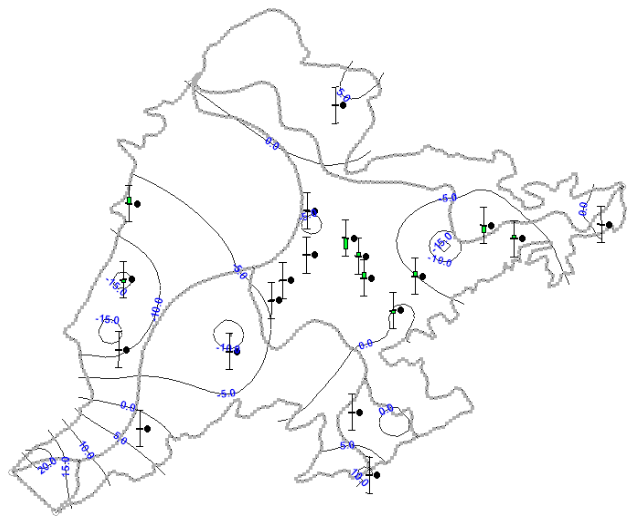

Fig. 13 The comparison between the results of model calibration and the observation values

4. Engineering Application

4.1 Project Description

This project is the large-scale pumping tests of group wells for the deep excavations of Taipei MRT near the Danshui River. The results of tests will be the design reference for the follow-up deep excavations of underground stations. The location of the site and the arrangement of wells are shown in Fig. 14 and Fig. 15, respectively.

The pumping rate for wells No.8, No.9, No.11, No.13, No.14, No.16, No.17, No.18, No.19, No.20, No.22, and No.24 is 4 (m^3/min); the pumping rate for wells No.12, No. 21, and No.23 is 3 (m^3/min); the pumping rate for wells No.10 and No.25 is 4 (m^3/min) at first but stop pumping in the middle time because of a breakdown.

The wells begin pumping in turn as follows: No.17→ No.25→ No.16→ No.8→ No.9→ No.14→ No.18→ No.24→ No.19→ No.23→ No.10→ No.13→ No.11→ No.12→ No.20→ No.22→ No.21. Four wells begin to work in the first stage (i.e. No.17, No.25, No.16 and No.8). While the groundwater table is stable, four wells are added to work in the second stage (i.e. No.9, No.14, No.18 and No.24). While the water table is stable again, additional four wells begin working in the third stage (i.e. No.19, No.23, No.10, No.13). While the groundwater table is more steady, the other wells work together in the final stage (i.e. No.11, No.12, No.20, No.22, No.21). After that, 17 wells in total are working at the same time and pumping continuously for 72 hours. When the pumping is finished, the recovery test begins for 24 hours.

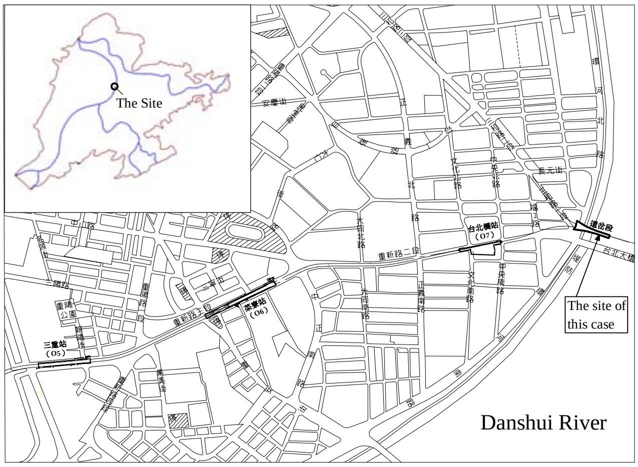

Fig. 14 The location of the pumping test of group wells for this case

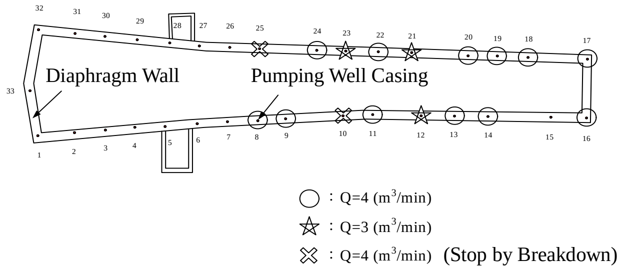

Fig. 15 The arrangement of the pumping test of group wells

4.2 Monitoring Data

During the pumping test of group wells, the monitoring drawdown of water pressures within Jingmei Formation (confined aquifer), by electronic piezometers installed at the positions of pumping wells, is about 25-43m (see Fig.16). The drawdown of water pressures within Jingmei Formation measured by electronic piezometers installed outside of the excavation zone is about 23-30m; the drawdown of water pressure at the Shongshan 3rd sub-layer is about 2-4m (see Fig.17). The observation wells are arranged at the distances of 50m, 100m, 200m and 400m outside of the excavation area, and the piezometers installed in the different depths for each well (i.e. Shongshan 5th sub-layer No.1, No.2, Shongshan 3rd sub-layer No.1, and Jingmei No.1). The basic information for each piezometer is listed in Table 2. The variations of groundwater table around the site during the pumping test of group wells are also presented in Table 3.

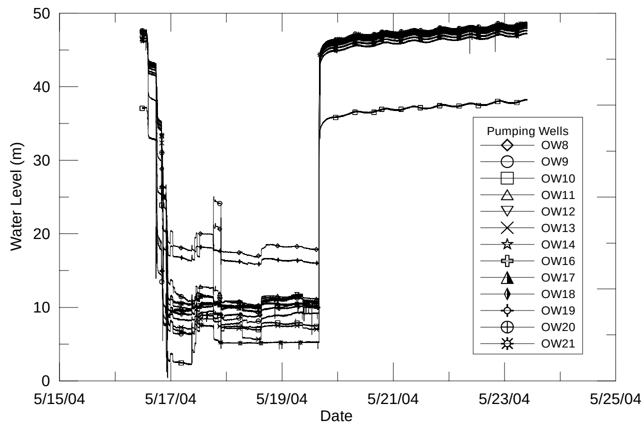

Fig. 16 The drawdown of groundwater table at the pumping wells during the pumping test

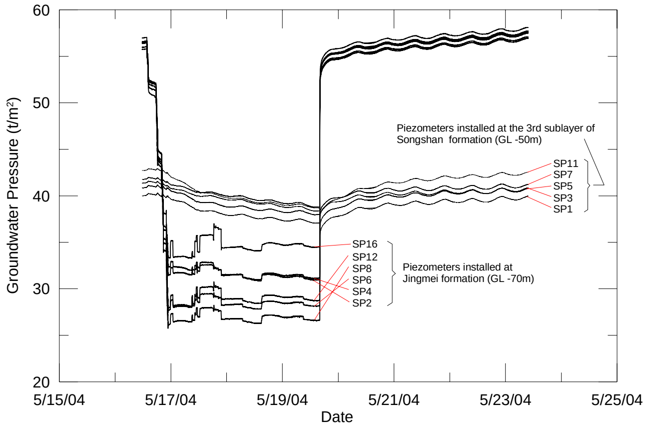

Fig. 17 The drawdown of groundwater table inside of the excavation area during the pumping test

Table. 2 The information of outside piezometers

Piezometer No.	Distance (m)	Installed Position and Depth (m)			
		Shongshan 5th sublayer (No.1)	Shongshan 5th sublayer (No.2)	Shongshan 3rd sublayer (No.1)	Jingmei Formation (No.1)
OW8-1	50	EL+100.1~ 98.1	EL+91.6~ 89.6	EL+66.0~ 64.0	EL+43.2~ 41.2
OW8-2	100	EL+100.4~ 98.4	EL+91.4~ 89.4	EL+65.9~ 63.9	EL+43.1~ 41.1
OW8-3	200	EL+99.9~ 97.9	EL+91.4~ 89.4	EL+65.2~ 63.2	EL+43.1~ 41.1
OW8-4	400	EL+98.2~ 96.2	EL+91.4~ 89.4	EL+65.8~ 63.8	EL+43.0~ 41.0

Table. 3 The variations of groundwater table

Piezometer No.	Distance (m)	Drawdown of Groundwater Table (m)			
		Shongshan 5th sublayer (No.1)	Shongshan 5th sublayer (No.2)	Shongshan 3rd sublayer (No.1)	Jingmei Formation (No.1)
OW8-1	50	0.2	0.1	3.8	6.0
OW8-2	100	0.2	0.1	3.2	5.0
OW8-3	200	0.3	0.1	2.2	4.8
OW8-4	400	0.1	0.1	1.0	3.2

4.3 Case Analysis

First, we can obtain the steady flow field of groundwater by the regional hydrogeological conceptual model of Taipei Basin, which was built up previously. Secondly, we can build a local scale model with the refined meshes around the site. The groundwater elevations computed from the regional model are applied as specified head boundary conditions to the local scale model. The detailed layer data, including elevations and geological parameters, are also interpolated from the regional to the local model. A more detailed representation of the local flow conditions, including the low capacity wells and barriers not included in the regional flow model can be constructed in the local scale mode (as shown in Fig. 18). Then, we execute the transient analysis by the MODFLOW package, according to the arrangement of wells and the pumping plan, to simulate the variation of groundwater elevations during the pumping test. Finally, the monitoring data of piezometers can be verified the validity and accuracy of conceptual model we built.

The results of simulation during the pumping test are shown in Fig. 19, and the comparison between simulations and observations is listed in Table 4. The results of analysis present that the error inside of the excavation area is smaller than the outside one. The reasons may be due to the uniformity of sediments, the validity of divisional hydraulic parameters, the leakage of aquitard (i.e. Shongshan 2nd clayey sub-layer) and so on. The computed influence radius of water pressure drawdown within the confined aquifer (Jingmei Formation) is about 2.5-3.0 km, as shown in Fig. 20.

Table. 4 The comparison between the results of simulation and the observation data

Position	Drawdown of Groundwater Pressure of Jingmei Formation	
	Results of Simulation (m)	Values of Observation (m)
Inside of Excavation Area	22~23	23~30
Distance of 50m	12	6.0
Distance of 100m	10	5.0
Distance of 200m	9	4.8
Distance of 400m	8	3.2

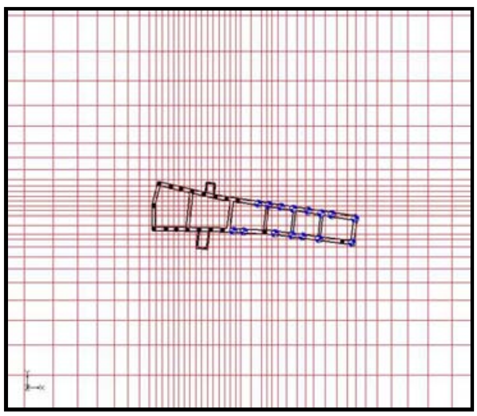

Fig. 18 The local-scale conceptual model

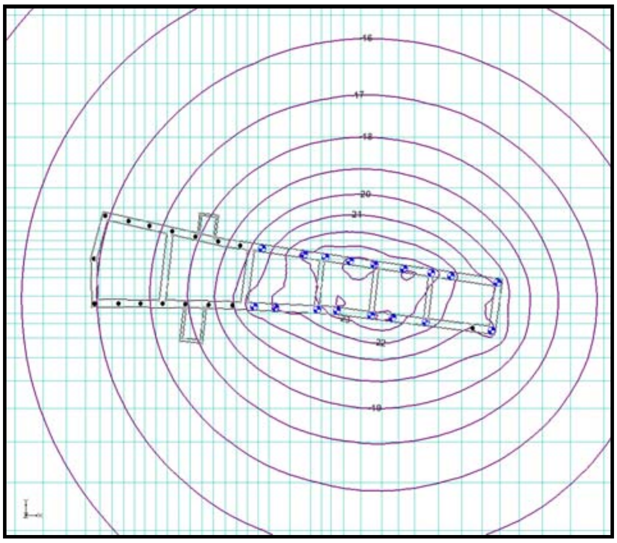

Fig. 19 The results of analysis for the pumping test of group wells

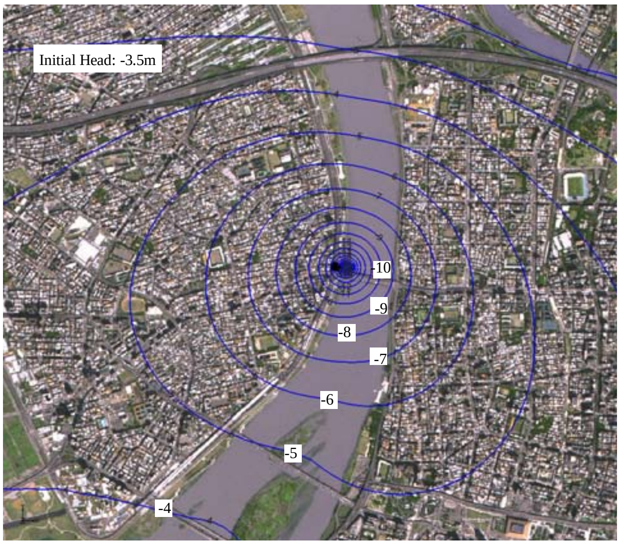

Fig. 20 The analysis of influence radius of groundwater pressure drawdown during the pumping test of group wells

5. Conclusions

The proposed 3D hydrogeological conceptual model of Taipei Basin has the greater validity and accuracy, and has other feature as follows: (1) the conceptual model is built up based on the 3D distributions of Shongshan formation and Jingmei Formation in space, (2) the assigned values of hydraulic parameters for aquifers are determined by the results of back-analysis of the pumping tests which were proposed by the previous researchers, (3) the groundwater recharge is determined by both the baseflow analysis of the main rivers in the Taipei Basin and the ratio of basin area to the watershed area, (4) the natural boundaries (such as rivers, faults and divides) are used to assign the boundary conditions (regarded as a constant-head, a variable-head, or a constant-flow boundary), (5) the present groundwater table are simulated by the imaginary wells and the pumping rates are determined by the automated parameter estimation, and (6) the monitoring data of the observation wells are applied to execute the model calibration.

This paper establishes the 3D hydrogeological conceptual model of Taipei Basin and applies it to predict the groundwater pressure drawdown successfully during the pumping test of group wells for the Taipei MRT deep excavations. However, the error of prediction outside of the excavation area is still significant due to uniformity of sediments, the validity of divisional hydraulic parameters, the leakage of aquitard, and the interference from other sites.

The proposed processes of building the hydrogeological conceptual model and the results of numerical analysis are very useful and valuable to design the pumping plan and execute the safety assessment in the related engineering.

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