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TECHNICAL COMMUNICATION

Evaluating Induced Fractures Between a Large Artificial Lake and an Aquifer-Coal Seam System: A Case Study in Tangshan Coal Mine, China

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Abstract The hydrogeology of the Tangshan coal mine is extremely complicated. There are at least 20 major faults, with the offset exceeding 50 m. A large artificial lake was created where mining-induced subsidence occurred; it was filled with groundwater pumped from the adjacent aquifers near the coal seams. In addition, there are two nearby rivers that are also believed to have significant groundwater and surface water interactions. Both the river system and the large lake could be a potential threat to a new mining operation in the deep no. 5 coal seam. An in-situ hybrid packer system was designed to measure the thickness of the fracture zone and a 3-D hydrogeological model of the coal seam, associated aquifers, artificial lake, and surface water was established to simulate the groundwater flow field to evaluate the potential impact of induced fractures between the lake and the aquifers and coal seams. The results indicated that the lake has an insignificant impact on the aquifers and coal seams, though it does influence the shallow quaternary aquifer in the study area. Further study is suggested to monitor the groundwater and surface water interactions between the lake and the shallow aquifer system.

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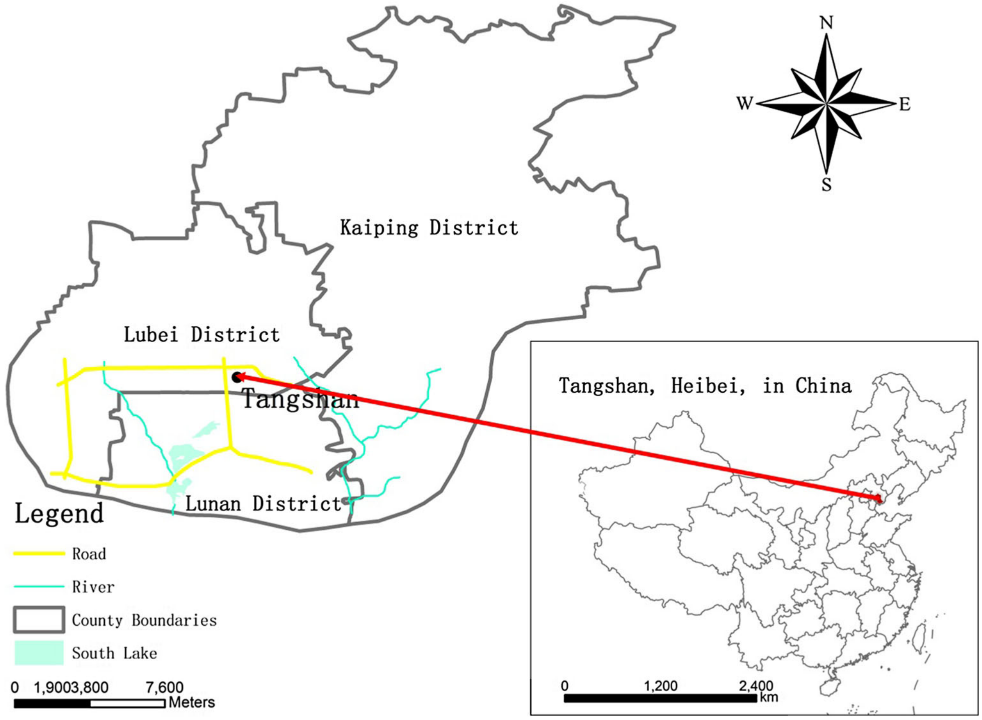
Introduction

Underground mining accounts for 97 % of coal production in China (China National Administration of Coal Geology 2001). With the depletion of near-surface coal and the preference for large-scale operations, most coal mining has moved to deeper coal seams. However, the earlier near-surface coal mining operations induced fractures that extended to the land surface and created land subsidence. When the subsidence stabilized years after mining ended in those shallow coal seams, large artificial lakes were created as a form of land reclamation. However, these mine subsidence lakes may present potential safety problems for mines now operating in deeper coal seams because lake water could enter the mines via the fractures.

The Tangshan coal mine is located in north China (Fig. 1) and is the oldest operating coal mine in China, with a 135 year history. The hydrogeology of the Tangshan mine is extremely complicated. There are at least 20 major faults, with the total offset exceeding 50 m. A large artificial lake (Danan Lake, approximate 11.5 km^2) was created where mining-induced subsidence occurred; it was filled with groundwater pumped from the aquifers near the coal seams. In addition, there are two nearby rivers that are also believed to have significant groundwater and surface water interactions (Dong and Wang 2010; Dong et al. 2012). Both the river system and Danan Lake could potentially threaten a new mine in the no. 5 coal seam (Dong et al. 2009). This study was undertaken to provide a scientific understanding of the groundwater flow field in the

Fig. 1 Location of the Tangshan coal mine



aquifer systems between the no. 5 coal seam and Danan Lake and assess the safety risk for the mine.

There have been many groundwater transient studies on analytical and numerical approaches to simulate mine water inflow (e.g. Anderson and Woessner 1992; Dong et al. 2012; Petrovskii and Sergeeva 1976; Veremchuk 1981). However, models do not always properly represent the interaction between an aquifer system and mining operations due to insufficient understanding of local geology (Dong et al. 2009; Yang et al. 2007).

Hydrogeology in Tangshan

There are seven major aquifer and aquitard systems in the Tangshan coal mine (Fig. 2). According to survey data of the no. 5 coal seam, the most influential aquifers are the confined aquifers no. 1, 5, and 7. This study analysed these

Fig. 2 Hydrogeology in the Tangshan coal mine

three aquifers and confining units (aquitard no.1 to aquitard no.3), which are briefly described below:

Aquifer No. 1 (Ordovician Limestone Aquifer)

The no. 1 aquifer is about 800 m thick. It has several outcrops in the modeling area due to its complicated syncline/anticline structure. Its hydrologic conductivity ranges from 0.018 to 22.638 m/d. The head fluctuated significantly between the dry season (March–April) and the rainy season (July–September). Since the fractures are well distributed in this aquifer, the head measurements from most of the monitoring wells have shown almost synchronized seasonal fluctuations. The average head contours, based on measurements from 2005 to 2010, are shown in Supplemental Figure 1, which accompanies the on-line version of this paper and can be downloaded for free by all IMWA members and journal subscribers.

Aquifer No. 5 (Sandstone Aquifer)

The average thickness of the aquifer is 16.74 m, ranging from 20.14 to 15.85 m. The hydrologic conductivity ranges from 0.0007 to 3.64 m/day. The storativity of the aquifer increases toward the south, though the storage of the whole system has significantly declined due to years of withdrawal due to mining operations beneath this aquifer system. The average head contours based on the measurement from 2005 to 2010 are shown in Fig. 3.

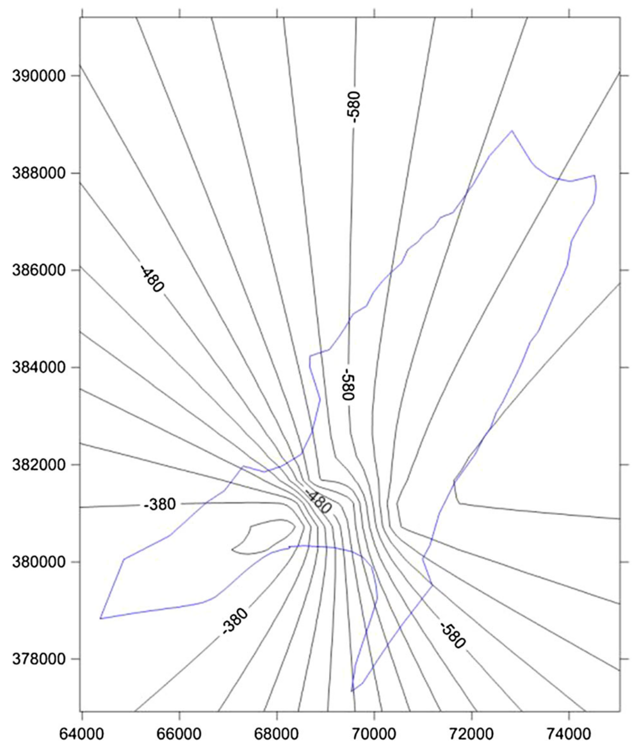


Fig. 3 The average head contours of aquifer no. 5 (sandstone aquifer) based on measurements from 2005 to 2010

Confining Unit (Three Aquitards Below Aquifer No. 5 and Above the No. 5 Coal Seam)

This confining unit consists of purple, light grey, and yellow bauxitic mudstone. The average thickness of the aquitard is 1.95 m, with a range of 2.4–1.51 m. The yellow part may contain pyrite and the purple contains elevated iron concentrations.

Aquifer No. 7 (Quaternary Sand and Gravel Aquifer)

The thickness of this aquifer ranges from 50.3 to 314.18 m. The hydrologic conductivity ranges from 1.28 to 9.129 m/day. The specific capacity of the aquifer ranges from 0.0729 to 0.894 L/s/m. Similar to aquifer no. 1, it has several outcrops in the study area and fractures are well distributed in this aquifer. Therefore, the head fluctuations in most of the monitoring wells in this aquifer have very similar patterns with those from aquifer no. 1. The average head contours based on measurements from 2005 to 2010 are shown in Supplemental Figure 2.

Methodology

In-situ Instrument Development

We have developed an in-situ hybrid packer system (HPS) to measure the vertical thickness of the induced fracture zone in the aquitard above the mining operation. The HPS consists of three parts: an air cell, a pipe system, and a control panel (Fig. 4). The two air cells, which are 1 m apart, are inflated with pressurised air in order to isolate a 1 m test section (the detector) of a borehole in the aquitard. The pipe system includes two pipes: a water pipe and an air pipe to inject water and air to the testing zone and air cells, respectively. The control panel is designed to control and monitor water and air pressure.

The Tangshan coal mine is the first field site for HPS operation after numerous laboratory calibration and small field tests. The vertical thickness of the fracture zone is measured in three steps:

1. The operator inserts the air packer section up into the far end of the pre-drilled borehole, which was about 80 m away in this study. The end of the borehole must be at least 2 m above the estimated fracture zone. The air cells are inflated until the cell pressure reaches the maximum operational limit required to ensure the isolation of the 1 m detector section.
2. Water is injected into the 1 m detector section and the flow rate is monitored during the injection. The injection pressure is always regulated 5 MPa greater than the static hydraulic static pressure at the end of the borehole and the injection test is complete when the injection flow rate no longer fluctuates.
3. After the termination of the water injection and the deflation of air cells, the detector section of the HPS is moved down 2 m and steps 1 and 2 are repeated until the device emerges from the borehole.

During such tests, the water flow rate in some sections might be large if the fracture is very well developed in those sections. In contrast, the water flow rate will be very slow if the detector section is above or below the fracture zone. The length of the fracture zone can be determined, within a 4 m range, by the water flow rate record. The

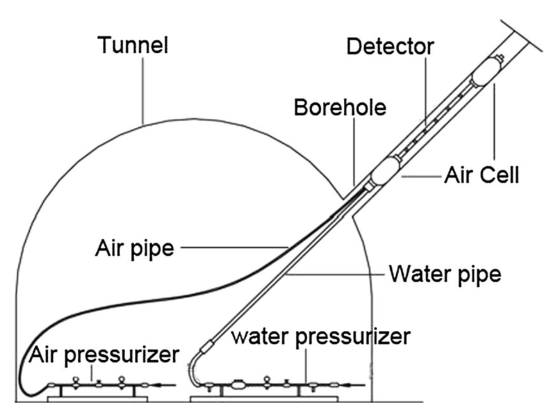


Fig. 4 The conceptual configuration and in-situ setup of the hybrid packer system (HPS)

vertical thickness of the fractured zone in the aquitard can be calculated based on the length of the fractured zone and the angle of the borehole. The water injection rate also can be used to estimate the hydraulic conductivity in the testing section (Gao et al. 2012).

In October 2012, a group of five researchers led by the lead author performed this procedure in two boreholes (T1 and T2) drilled into the aquitard from the underlying no. 5 coal seam, at a depth of 1,300 m from the land surface. The operation required approximately 12 h per borehole.

Numerical Simulation Using MODFLOW-2005

Hydrogeological data for the no. 5 coal seam in Tangshan are available since 1978 in Autocad and Longruan GIS format. Those data were recently converted to Shapefile using ArcGIS process for the boundary conditions and hydrogeology characteristics to establish a MODFLOW-2005 (Harbaugh 2005) model for groundwater flow simulation. MODFLOW is a three-dimensional finite-difference groundwater model that was first published by the U.S. Geological Survey (USGS) in 1984. MODFLOW-2005 is the most current release of MODFLOW that simulates steady and transient subsurface flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. We used a 64-bit version Groundwater Vistas 6 (GWV6) as the pre- and post-processor of the MODFLOW-2005 model to create multiple hypothesis models to simulate various conditions with the Danan Lake, surface water features, and seasonal groundwater fluctuation.

Results

The Induced Fracture Zone Thickness

The T1 borehole was drilled at an angle of 23° and a length of 82 m. The HPS was operated at inflation air pressures of 2.6–2.9 MPa and water injection pressures of 0.60–1.00 MPa. After 12 h tests, the flow rates in the borehole in the aquitard were between 62 and 106 L/min (Fig. 5).

The T2 borehole was drilled at an angle of 23° and a length of 86 m. The HPS was operated at inflation air pressures of 4.0 MPa and water injection pressures of 0.4 to 0.6 MPa. After 12 h tests, the flow rates in the borehole in the aquitard were between 4 and 8 L/min (Fig. 6).

$$H_f = H - H_b$$

where H_f is the height of fractured zone; H is water pressure, and; H_b is the elevation of the tunnel bottom. Therefore, for T1, $h_{f1} = 46.72 - 35.27 \times \cos 23 \times tg5 - 1.8$ or $46.72 - 2.84 - 1.8 = 42.08$ m and for T2, $h_{f2} = 46.72 - 38.25 \times \cos 23° \times tg5° - 1.8$ or $46.72 - 3.08 - 1.8 = 41.84$ m. The maximum height of the fractured zone is therefore 42.08 m.

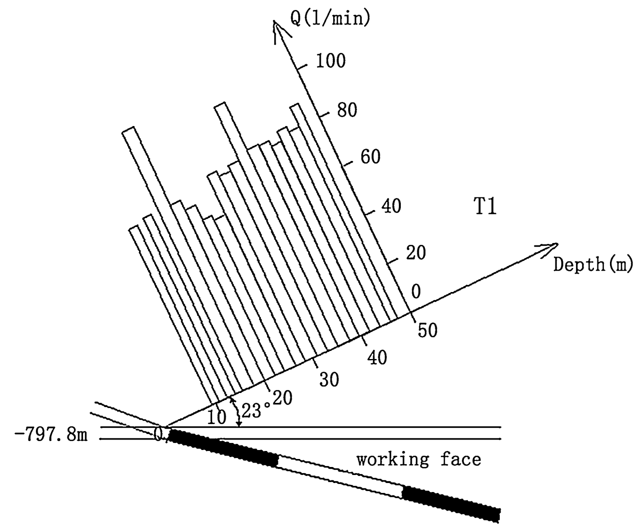


Fig. 5 The injecting water flow rates (L/min) from the HPS along borehole T1

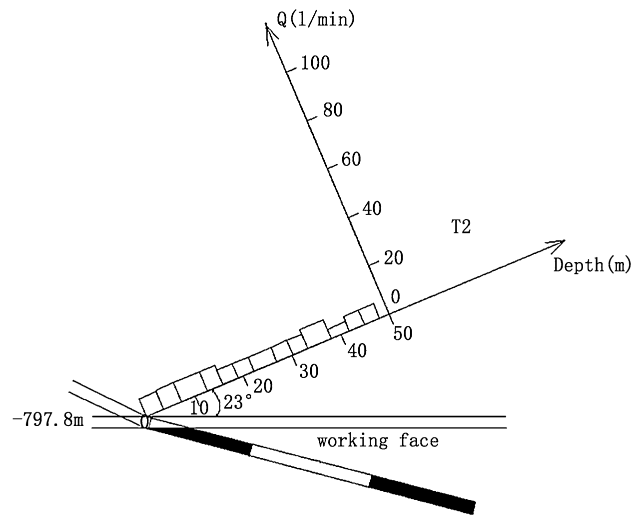


Fig. 6 The injecting water flow rates (L/min) from the HPS along borehole T2

Based on operational experience in China, the suggested minimum thickness between the bottom of an aquifer and the top of a mine's working face is 80 m to minimize the risk from induced fractures. Since the measured fracture thickness (42.08 m) from the HPS test is much less than 80 m, a numerical simulation of the groundwater flow field was undertaken to provide a better understanding of the effect of the higher hydraulic conductivity due to fractures. In the following groundwater model, the thickness of the aquifer no. 5 was reduced proportionally, and the hydraulic conductivity was increased from the original 0.1 to 0.6 m/day, based on the new HPS results. The difference between the interpolated heads from the observations (Fig. 3) and the simulated heads (Fig. 7) in the mining operation area are within 20 m of each other, which is much less than the operational tolerance. Therefore, it indicates that the updated fracture aquifer thickness and the hydraulic conductivity will have an insignificant effect on the safety of the mining operation.

The Potential Impact of the Groundwater Flow Field from Danan Lake

Two models were constructed based on two scenarios: with and without Danan Lake (Figs. 7 and 8, respectively), which was simulated by a constant head boundary condition. A comparison of the two figures shows no significant change on the head contours at aquifer no. 5, which indicates that the artificial lake has a negligible effect on mine safety. Moreover, the mine water flux is not increased. Nevertheless, the mine operator has been advised to continue observing fracture development in aquifer no. 5 by monitoring the seepage rate at the working face, because mining might induce more fractures.

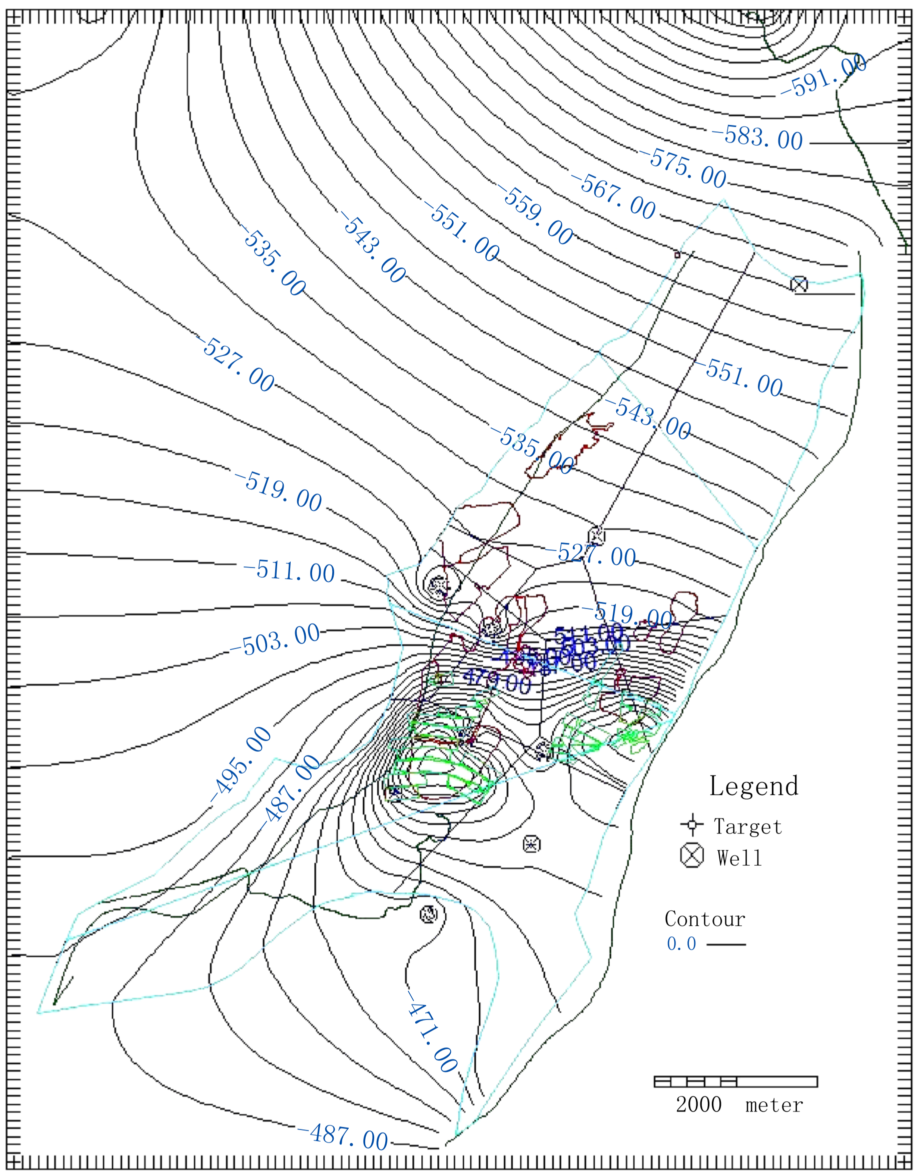


Fig. 7 The simulated head contours for aquifer no. 5

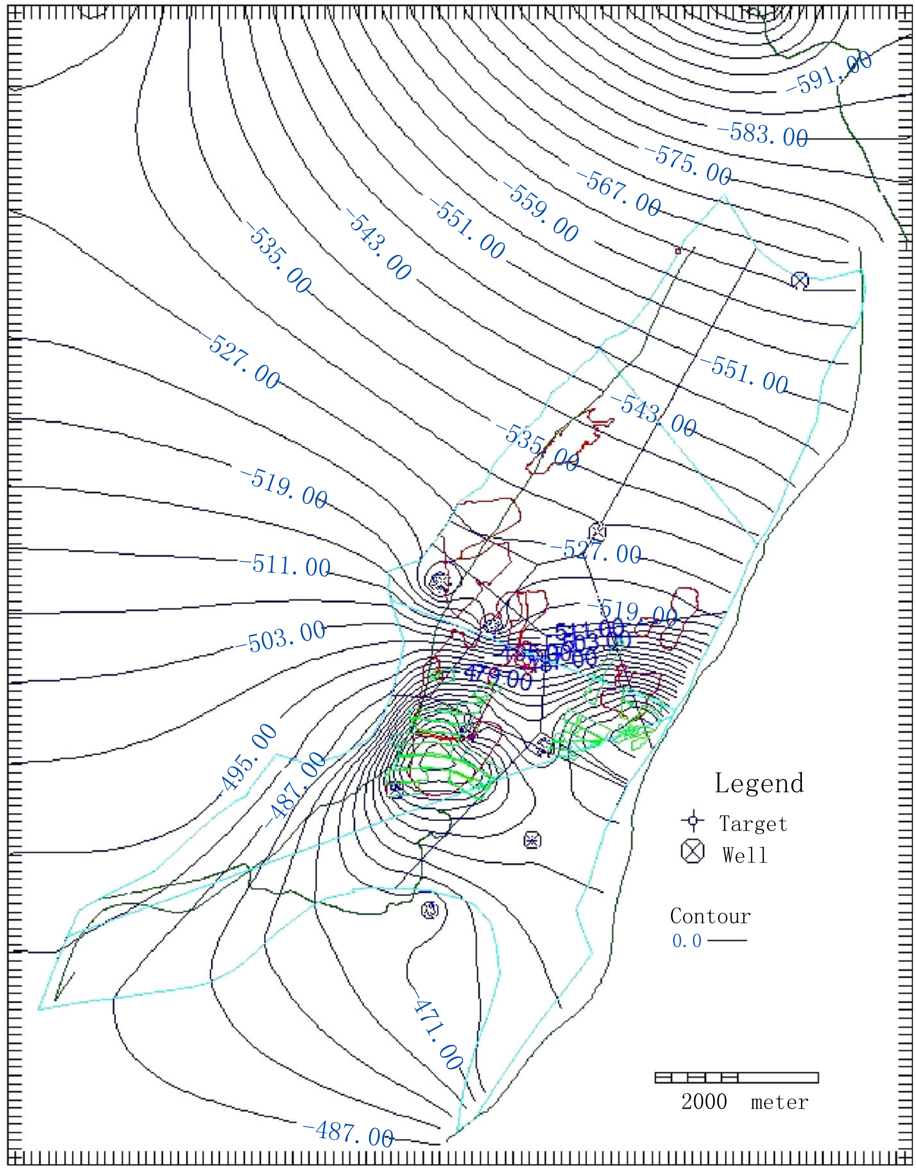


Fig. 8 The simulated head contours for aquifer no. 5 without a constant head boundary condition for Danan Lake

The vertical head distributions from numerical simulations with and without Danan Lake as a constant head boundary condition have been thoroughly investigated. For example, the vertical head distributions at row 50 (Fig. 9) show insignificant differences between the two models, though there are some minor difference on the [left and middle] of the row at stress period 49. Although the differences are in the negligible tolerance range from the mining operation safety standard, it does indicate an effect from the combined stress from the induced faults and the hydraulic pressure from Danan Lake.

Discussion

Coal has been mined in the Tangshan region for 135 years, using the traditional top to bottom method, which means that deeper coal seams were mined right after the coal seam above it was depleted. Therefore, dewatering the aquifer above a coal seam is extremely important for the safety of the mining operation. The no. 5 coal seam is a relatively new mining operation in the Tangshan region. In the modeling area, the no. 1 to 4 coal seams were not mined due to insufficient seam thickness, and the no. 9 coal seam, which is beneath the no. 5 coal seam, is the next mining operation planned in this area.

The daily monitoring network in the no. 5 coal seam indicates very limited vertical flow movement in the studied area. The site investigation and numerical simulations indicate that the induced fractures in the aquitard above the no. 5 coal seam impose an insignificant safety concern on current mining operation from Danan Lake. Nevertheless, it has considerably changed the groundwater

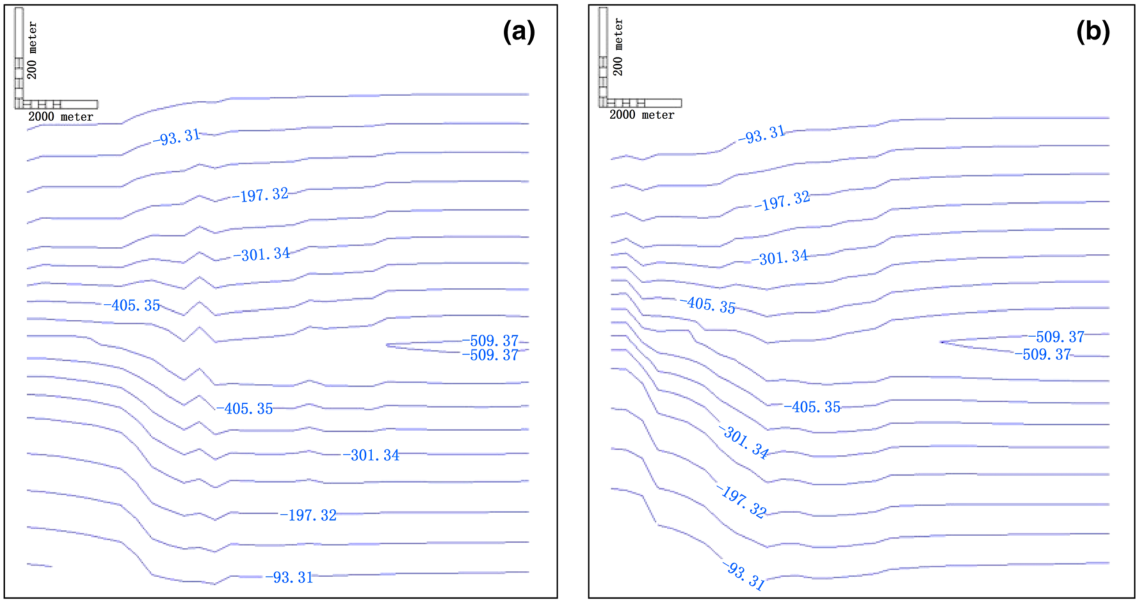


Fig. 9 The vertical head distributions at row 50 at stress period 49 (as shown in Fig. 8) with and without Danan Lake, as simulated by a constant head boundary condition

flow field in aquifer no. 5, which is above the no. 5 coal seam. Continuous high pumpage from the aquifer no. 5 causes the water level in it to keep decreasing dramatically. Figure 10 shows a simulation after pumping for 100 years. Figure 10a shows the dewatering cells from aquifer no. 5 to the no. 5 coal seam, including the aquitard at the pumping well with the largest pumping rate. This cone of depression (Fig. 10b) might increase the size of the dewatering zone, which could potentially disrupt the groundwater flow path from north to south in the area.

With its 135 years of mining history, the induced fractures in the previous mined areas have been gradually compacted and consolidated as water-filled channels opened and closed (as a result of 100 years of exploitation). Experimental data from the HPS test in the no. 5 coal seam showed that the height of the water fractured zone is only 42 m, which was less than the expected 80 m. Aquifers no. 5 and 7 might have certain degrees of connectivity, bypassing the aquitard through the faults, which will require further investigation.

Based on historical observations of the stage level of Danan Lake, the fluctuation of the lake level has been within the range of climate variation and correlates with precipitation and evaporation. Therefore, the induced fractures were not expected to connect Danan Lake with the aquifers and coal seams, although there was no quantitative study before this study. The numerical simulation and the calibration show no significant flux increase in the deep aquifers and coal seams, with low errors against calibrating targets. The major stress modifying the vertical and horizontal groundwater flow fields is the pumpage, based on the transient simulation. However, the flux in the shallow quaternary aquifer seems to be increasing in the simulation as well as from field observations of rising levels in local domestic wells from the shallow quaternary aquifer. It is possible that the groundwater and surface water interactions between the large artificial lake and the shallow quaternary aquifer are increasing. Further study of the groundwater and surface water interactions near the Danan Lake is highly recommended.

Conclusion

This work combined: (1) an in-situ hybrid packer system (HPS) to measure the thickness of fracture zone, and (2) calibrated numerical modelling to simulate the 3-D groundwater flow field to evaluate the impact of induced fractures between a large artificial lake and underlying aquifers and coal seams. The in-situ HPS successfully provided quantifiable measurements of the rock deformation that could be used as the input parameters in the numerical groundwater flow model. Then the numerical model was used to provide an accurate assessment of the effect of the induced fractures based on the simulated 3-D flow field and flux, as calibrated with field observations. The results indicated that Danan Lake has an insignificant effect on the deeper aquifers and coal seams but noticeably influences the shallow quaternary aquifer in the study area. Further study is strongly suggested to monitor ground- and surface-water interactions between Danan Lake and the