Multiple tests for identifying hydraulic conductivities of south and north boundary faults at Ganhe field, Huozhou Coal Electricity Group Co., Ltd, China

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ABSTRACT
Hydraulic conductivities of faults influence the mining design and safety of a coalmine badly. Results of field and indoor tests on hydraulic conductivities of the boundary faults in Ganhe coalfield in China are illustrated. According to the drilling engineering, Xiatuanbai fault and F1 fault near north boundary and Xiazhangduan fault near south boundary are all transtensional normal faults. Furthermore, there formed obvious fracture zones in the Ordovician strata of both sides of the faults with respect to its influence and their water conductivities are all obvious. Results of the pumping test show there are obvious hydraulic connectivities between Fengfeng Formation aquifers and Upper Majiagou Formation aquifers on both sides of the three boundary faults. Therefore, they are all partial water-conductive faults. Results of connectivity tests also show there are obvious hydraulic connectivities in the karst aquifers on both sides of Xiatuanbai fault and Xiazhangduan fault and they are both partial conductive faults. Finally, differences on hydrochemical and stable isotope features between both sides of the three faults are all inconspicuous and the same results on the hydraulic conductivities of the three faults are obtained. The above comprehensive conclusions provide a strong basis for water disaster control of Ganhe mine.

1. Introduction
Hydraulic conductivities of faults influence the mining design and safety of a coalmine badly (Song and Renwu 1999; Baolin et al. 2002; Chen et al. 2008; Hui et al. 2017). Therefore, identification of the hydraulic conductivities of faults at a coalmine
is very essential for the water inrush prevention, damage mitigation and safely mining (Qiang et al. 2013a, 2013b; Qiang 2014; Cui et al. 2015; Haiyan et al. 2017). At present, hydrogeological drilling, transient electromagnetic method, hydrogeological well logging, pumping test, hydraulic connectivity test, groundwater geochemistry and isotopic techniques are widely applied together to identify hydraulic conductivities of faults and to obtain more explicit hydrogeological conditions of a coalmine for its mining safety (Qiang and Daiyong 2009; Jiaying et al. 2010; Yuhe et al. 2010; Jinzhu and Youxin 2013; Rongfeng et al. 2013).

As one of the major coalmines of Huozhou Coal Electricity Group, the mining of 2nd and 10th coal seam of Ganhe coalmine is threatened badly by the groundwater from the underlying confined aquifer in Ordovician limestone (Shenju et al. 2016). Furthermore, Xiatuanbai fault, F1 fault and Xiazhangduan fault, being the boundary faults of the coalmine, had all penetrated the aquifer (Wang 2015). Hence, hydraulic conductivities of the three faults are very important issues when the adjacent mining and the associated water inrush evaluation and control are conducted.

Consequently, comprehensive techniques mentioned above were conducted and the results were discussed detailedly in this paper to identify the hydraulic conductivities of the three faults to provide some supports for the mining safely and its associated water inrush prevention.

2. Analysis based on hydrogeological drilling

2.1 Distribution of the boreholes in the coalfield

As shown in Figure 1, the north boundary of Ganhe coalfield consists of Xiatuanbai fault and F1 fault that locates south to the former one and is paralleled to it. Xiazhangduan fault is the south boundary of the coalfield. Boreholes for identifying features of these three faults are GK1, GK2, GK3, GK4, GK5 and GK6.

![Figure 1. Distribution of the south and north boundary faults of Ganhe coalfield.](image)
2.2 Fault spatial characteristics

Xiatuanbai fault locates in the north boundary of Ganhe coalfield. It is a transtensional normal fault and its length is about 26 km in total. The fault strikes NE direction and dips to the south-east in total in the coalfield, as shown in Figure 1, and its dip angle is about 70°. Valleys cut deeply and cliffs form along the fault zone. Bedrocks appear partially and landforms and rock strata between both sides of the fault zone are different. Striations, extrusions and crushed zones are also obviously. Throws along the fault are different and that near the west of the coalfield is about 300 m. The throw near the middle part of the coalfield is about 364 m, as shown in Figure 2(a), and that near the east of the coalfield is about 350 m, as shown in Figure 2(b).

F1 fault is nearly paralleled to Xiatuanbai fault in total in the coalfield and the normal distance between them is about 150–200 m. The fault is buried by loess and its surface features are not apparent. It is also a transtensional normal one and the dip angle of the fault plane is about 70°. Throws along this fault are also varying and that near the west of the coalfield is about 90 m. The throw near the middle part of the coalfield is about 167 m, as shown in Figure 2(a), and that near the east of the coalfield is about 116 m, as shown in Figure 2(b).

As south boundary of Ganhe coalfield, as shown in Figure 2(c), Xiazhangduan fault also strikes NE direction and dips to the south-east in total. It is also a transtensional normal fault. Its total length is about 14 km and the dip angle of its fault plane is also about 70°. Its throws are about from 100 m to 35 m along the fault from the west to the east.

2.3 Hydraulic conductivities of the faults

As far as Xiatuanbai fault and F1 fault are concerned, their fault planes always opened in a small scale and were almost filled with selvage. Fractures seldom generated nearby and therefore the hydraulic conductivities are weak relatively. However, as shown in Figure 2(a) and Figure 2(b), footwalls of the faults consist of brittle karst

![Figure 2](image-url)

Figure 2. (a) A profile map of north boundary of Ganhe coalfield based on GK1 and GK2 borehole; (b) a profile map of north boundary of Ganhe coalfield based on GK3 and GK4 boreholes; and (c) a profile map of south boundary of Ganhe coalfield based on GK5 and GK6 boreholes.
strata formed in Ordovician or Cambrian Period. With respect to the influences from the faults, well-opened traction fractures generated in the strata and therefore they possessed strong hydraulic permeabilities. As a result, strong hydraulic connections between the footwall karst strata and the hanging wall strata mainly consisted of brittle fractured karst strata and fractured sandrocks generated subsequently. At present, lateral recharge karst groundwater from the footwalls is one of the main filling sources for coal seams in the hanging walls and the entire coalmine.

On mining the coal seams in the hanging wall near F1 fault, the lateral recharge groundwater from footwalls of F1 fault and Xiatuanbai fault will be a great threat.

Finally, as far as Xiazhangduan fault is concerned, as shown in Figure 2(c), due to its relative small-scale throw, its hydraulic conductivity is different from that of the above two faults to some extent and so is the recharge relationships between the strata composing the footwalls and the hanging walls of the above two faults. First, coal-bearing strata of two sides of the fault are closely connected with respect to the small-scale throw. There is a weak hydraulic connection between two sides of the fault near the coal-bearing strata. Second, there is a strong hydraulic connection between two sides of the fault near the karst strata mainly consisted of Ordovician limestone.

3. Analysis based on hydrogeological well logging

The well logging was conducted in borehole GK2 as shown in Figure 1.

According to the results, there is an obviously fracture zone locating in the Ordovician limestone beneath F1 fault plane and its height is about 10 m. Some obvious features of the fracture zone are low electrical resistivity, high natural gamma and low natural density. The fracture zone makes groundwater flow fluent in the karst strata nearby.

4. Analysis based on pumping tests

4.1 Locations of the pumping tests

Group-well steady-state flow pumping tests were conducted for four times near north boundary of Ganhe coalfield. As for the two pumping tests in west part near the north boundary, borehole GK2 was used to pump and boreholes GK1, GK3 and GK4 were used to monitor water tables. As for another two pumping tests in east part near the north boundary, borehole GK4 was used to pump and boreholes GK2 and GK3 were used as water-table monitoring borehole.

Steady-state flow group-well pumping tests were conducted twice near Xiazhangduan fault locating in south boundary of the coalfield. One test was held in Fengfeng Formation limestone aquifer and another one was held in Upper Majiagou Formation limestone aquifer. Borehole GK6 was taken as the pumping well and GK5 was taken as the observation borehole.

4.2 Results of the tests near the north boundary

With respect to relevant requests, a maximum aquifer drawdown in the pumping well matched the peak capacity of the pumping equipment should be met in a test.
The testing aquifers were the Ordovician limestone strata of Fengfeng Formation and Upper Majiagou Formation. The water-table monitoring should be well conducted in the process of the pumping.

First, there appeared a maximum water-level drawdown of 28.40 m in GK2 pumping borehole when a group-well pumping test was conducted in Fengfeng Formation aquifer. The test lasted for 72 hours in total and there began to appear a water-level drawdown up to 6 cm in GK1 observation borehole from the 53rd hour. The water table in GK1 borehole recovered to its initial level after the pumping was over for 9 hours. The calculated specific capacity was 0.283 l/s m. The result shows there are well hydraulic connections in nearby Fengfeng Formation limestone aquifers cut by Xiatuanbai fault and F1 fault. The traction fractured zones induced by the two faults mainly contributed the hydraulic connections.

Second, the maximum water-level drawdown reached 14.96 m in GK2 pumping borehole when a mixed-layer group-well pumping test was conducted in Fengfeng Formation and Upper Majiagou Formation aquifer. The test lasted for 168 hours in total. On the pumping test beginning, the water-level drawdowns in observation boreholes GK1, GK3 and GK4 were started to be measured once every 30 minutes. There appeared a steady peak water-level drawdown of 8 cm when the pumping test lasted for 85 hours. However, the water-level drawdowns in GK3 and GK4 observation boreholes are not apparent. The specific capacity is 0.538 l/s m. It is larger than that of the above test, that is 0.283 l/s m. This result shows there are also well hydraulic connections in nearby Fengfeng Formation and Upper Majiagou Formation aquifers cut by Xiatuanbai fault and F1 fault.

Finally, another two group-well pumping tests were conducted in east part of north boundary. Borehole GK4 was taken as the pumping well. Boreholes GK2 and GK3 were taken as the observation wells. One group-well test was held in Fengfeng Formation aquifer and another mixed-layer test was held in Fengfeng Formation and Upper Majiagou Formation aquifers. In the former test, the specific capacity was 0.161 l/s m and the peak water-level drawdown was 39.10 m in borehole GK4. The steady peak water-level drawdown in GK3 observation well was 8 cm after the test lasted for 46 hours. In the latter test, the specific capacity was 0.381 l/s m and the peak water-level drawdown was 18.31 m in borehole GK4. The steady peak water-level drawdown in GK3 observation well was 5 cm. The results show there are also well hydraulic connections in nearby Fengfeng Formation and Upper Majiagou Formation aquifers cut by Xiatuanbai fault and F1 fault.

All the above results, as shown in Table 1, show Xiatuanbai fault and F1 fault in north boundary of the coalfield are water conductive.

4.3 Results of the tests near the south boundary

The calculated specific capacity of Fengfeng Formation aquifer was 0.55 l/s m in the first pumping test. The peak water-level drawdown in borehole GK6 was 17.81 m and that in GK5 observation borehole reached 0.50 m. The results show there exists well hydraulic connection between nearby Fengfeng Formation aquifers in both sides of Xiazhangduan fault.

The specific capacity of Upper Majiagou Formation aquifer was 3.25 l/s m in the second pumping test. The peak water-level drawdown in borehole GK6 was 3.75 m
Table 1. Results of group-well pumping tests of north boundary faults in Ganhe coalfield.

| Pumping well | Location | Recharge thickness/m | Initial elevation of water table/m | Final elevation of water table/m | Duration/h | Steady-state pumping duration/h | Dynamic water table/m | Drawdown/m | Flow rate/L s⁻¹ | Observation well |
|--------------|----------|----------------------|-----------------------------------|-----------------------------------|------------|--------------------------------|----------------------|------------|----------------|------------------|
| GK2          | O₂f      | 4.35                 | 518.22                            | 518.18                            | 72         | 24                              | 58.81                | 28.40      | 8.03           |                  |
|              | O₂f O₃f  | 15.50                | 518.22                            | 518.17                            | 168        | 75                              | 45.37                | 14.96      | 8.05           |                  |
| GK4          | O₂f      | 8.09                 | 518.12                            | 518.09                            | 15         | 175.78                          | 39.10                | 6.28       |                |                  |
|              | O₂f O₃f  | 15.59                | 518.10                            | 518.10                            | 168        | 12                              | 154.75               | 18.31      | 6.98           |                  |

| Observation well | Number | Distance to pumping well/m | drawdown/m |
|------------------|--------|--------------------------|------------|
| GK1              | 354.3  |                         | 0.06       |
| GK4              | 1297   |                         | ≈0.00      |
| GK1              | 354.3  |                         | 0.08       |
| GK3              | 1375   |                         | 0.00       |
| GK4              | 1297   |                         | ≈0.00      |
| GK3              | 414.9  |                         | 0.08       |
| GK2              | 1297   |                         | ≈0.00      |
| GK3              | 414.9  |                         | 0.05       |
| GK2              | 1297   |                         | ≈0.00      |
and that in GK5 observation borehole reached 0.05 m. The water level in GK5 borehole recovered slowly to its normal after this pumping test was over. The results show there is some hydraulic connection between nearby Upper Majiagou Formation aquifers in two sides of Xiazhangduan fault. However, the hydraulic connection is not as strong as that of Fengfeng Formation aquifers.

All the above results, as shown in Table 2, show Xiazhangduan fault in south boundary of the coalfield is water conductive.

5. Analysis based on hydraulic connectivity tests

5.1 Project for the connectivity tests

Hydraulic connectivity tests were conducted twice. The first one operated in GK3 and GK4 borehole was to assess hydraulic connectivity of Xiatuanbai fault and the second one operated in GK5 and GK6 boreholes was to assess hydraulic connectivity of Xiazhangduan fault. NaCl was used as a tracer during the two tests to identify the connectivities of the two faults. In test one, NaCl was put into GK3 borehole and electrical conductivity of the water in GK4 borehole was measured. In test two, NaCl was put into GK5 borehole and electrical conductivity of the water in GK6 was measured.

5.2 Results of the tests

In test one, GK4 borehole began to be pumped at 14:00 on 18 March 2016. At 17:00 on 23 March one-tonne NaCl was put into GK3 borehole and three hours later, the water in GK4 borehole began to be sampled every two hours until 16:00 on 26 March. The determination results on electrical conductivities of the water samples showed there was a relative high value of $0.147 \ \Omega \cdot m$ at 10:00 on 24 March and a peak value of $0.151 \ \Omega \cdot m$ at 0:00 on 25 March in Figure 3(a). Then, the values came back to the normal to the end of the test.

In test two, GK6 borehole began to be pumped at 16:00 on 14 December 2016. At 16:00 on 15 December, one-tonne NaCl was put into GK5 borehole and at 10:00 on 20 December, electrical conductivity of the water sample taken in GK5 borehole reached $1.06 \ \Omega \cdot m$ as shown in Figure 3(b). There appeared an obvious jump on the curve in Figure 3(b) at the same time.

The jumps appeared on the curves in Figure 3(a) and Figure 3(b) indicated NaCl components of the water samples taken in GK4 and GK6 observation borehole increased. It can also be shown the karst water from each side of Xiatuanbai fault and F1 fault is connective. Similarly, the karst water from each side of Xiazhangduan fault is also connective.

6. Analysis on hydrochemical characteristics

Hydrochemical determination of water samples taken from GK1, GK2, GK3 and GK4 boreholes was conducted.

The results show there is no obvious difference on hydrochemical characteristics of the groundwater from the karst aquifers located two sides of Xiatuanbai fault and
Table 2. Results of group-well pumping tests of south boundary faults in Ganhe coalfield.

| Number | Location | Recharge thickness/m | Initial elevation of water table/m | Final elevation of water table/m | Duration/h | Steady-state pumping duration/h | Dynamic water table /m | Drawdown/m | Flow rate/L s⁻¹ |
|--------|----------|----------------------|-----------------------------------|----------------------------------|------------|-------------------------------|-----------------------|------------|----------------|
| GK6    | O₂f      | 14.35                | 515.99                            | 515.99                           | 53         | 30                            | 14.06                 | 17.81      | 9.83          |
|        | O₂s      | 14.37                | 515.99                            | 515.99                           | 48         | 40                            | 0                     | 3.75       | 12.20         |
| GK5    | O₂f      | 380.25 m             | Its distance to GK6 borehole is    | Its water table began to down    | 5 hours    | 0.50 m                        | 37 hours later        | 0.05 m     | 3.75 m in     |
|        | O₂s      | Its distance to GK6 borehole is 380.25 m. Its final drawdown was only 0.05 m with respect to the drawdown of 3.75 m in GK6 pumping borehole. | 37 hours later                     | 0.50 m after 5 hours and reached a peak drawdown of 0.50 m 37 hours later. Its water table began to recover 2 hours later after the pumping ended and recovered its initial water table 16 hours later. | 37 hours later        | 0.05 m     | 3.75 m in     |
F1 fault. For example, the main hydrochemical component is \( \text{SO}_4^{2-} + \text{HCO}_3^- + \text{Ca-Mg} \) and the scope of total dissolved solid is \( 0.59 \sim 0.92 \text{ g/L} \). The results indicate the karst aquifers from two sides of the faults are connective, to some extent.

According to hydrochemical determination results of water samples taken from GK5 and GK6 borehole, there is also no obvious difference on hydrochemical properties of the groundwater from the karst aquifers located two sides of Xiazhangduan fault. The results also indicate the karst aquifers from two sides of the fault are connective, to some extent.

### 7. Analysis on water environmental isotopes

#### 7.1 Project for the connectivity tests

Analysis of water environment isotopes can provide a rich insight for identifying recharge sources and passages of groundwater (Xiurong et al. 2015). In this paper, the analysis is also very significant for determining hydraulic connectivity between the groundwater from the karst aquifers located two sides of the faults. The project for the tests including sample locations and number of the samples is shown in Table 3.

#### 7.2 Results of the tests

Determination results on environmental isotopes of karst groundwater samples are also shown in Table 3. The results indicate components of stable isotopes including \( \delta^D \) and \( \delta^{18}O \) of karst groundwater samples from the Ordovician limestone aquifers

![Figure 3](image). (a) Electrical conductivity curve of the connectivity test operated in GK3 and GK4 boreholes; (b) electrical conductivity curve of the connectivity test operated in GK5 and GK6 boreholes.

| Locations                      | Formation | Number | \( \delta^D \) (%) | \( \delta^{18}O \) (%) |
|-------------------------------|-----------|--------|-------------------|------------------------|
| The footwall of Xiatuanbai fault | \( O_2f \) | 2      | Minimum -76, maximum -76 | Minimum -10.4, maximum -10.7, -10.55 |
|                               | \( O_2f + O_2s \) | 1    | -78              | -10.9                  |
| The hanging wall of Xiatuanbai fault | \( O_2f \) | 2      | Minimum -80, maximum -81 | Minimum -11.2, -11.4, -11.3 |
|                               | \( O_2f + O_2s \) | 2    | -80 to -81, maximum -80.5 | -10.9, -11.2, -11.05 |
| The footwall of Xiazhangduan fault | \( O_2f \) | 1      | -85              | -11.6                  |
|                               | \( O_2s \) | 1    | -81              | -11.3                  |
| The hanging wall of Xiazhangduan fault | \( O_2f \) | 1      | -80              | -11.1                  |
|                               | \( O_2s \) | 1    | -78              | -11.4                  |
located both sides of the coalfield boundary faults are near equal. It is also indicated rainfall is a mutual recharge source for the karst aquifers located both sides of the faults with respect to their near-equal component values of groundwater environmental stable isotopes between rainfall and the karst groundwater.

As a result, the karst aquifers from two sides of the north and south boundary faults are connective and the faults are conductive to some extent with respect to the groundwater environmental isotopes analysis.

8. Conclusions

Hydraulic conductivities of faults are very significant for the nearby mining design and safety at a coalmine. Hydrogeological drilling and related tests were conducted to identify the hydraulic conductivities of north and south boundary faults in Ganhe coalfield for subsequent possible water inrush prevention and long-term mining safely. In general, the following conclusions can be drawn.

1. With respect to results of the hydrogeological drilling, Xiatuanbai fault, F1 fault and Xiazhangduan fault near the coalfield boundary are all transtensional normal faults. The karst aquifers located both sides of the above faults are all connective to some extent and the three faults are all partial conductive.

2. According to results of well logging in GK2 borehole, there exists an about 10 m fracture zone located in the Ordovician limestone beneath F1 fault plane. The fracture zone facilitates the hydraulic conductivity of the fault.

3. Results of group-well pumping tests show Fengfeng Formation and Upper Majiagou Formation karst aquifers located both sides of the three boundary faults are all obvious connective and the three faults are all partial conductive.

4. Results of hydraulic connectivity tests show the karst aquifers located both sides of Xiatuanbai fault and Xiazhangduan fault are all connective and the two faults are partial water conductive.

5. Results of hydrochemical analysis and stable isotopes analysis of groundwater from the karst aquifers located both sides of the boundary faults show there is no obvious difference with respect to their properties. Three boundary faults are all partial water conductive.

Disclosure statement

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