Evaluation of influence of mining cracks on reservoir leakage

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Abstract: Combined with the engineering geological conditions and the goaf occurrence of Hongyanhe Reservoir in Binzhou City, the distribution characteristics of the fissure zone in the edge of goaf were explored by field test. The influence of mining fissure on reservoir seepage were evaluated on the basis of analyzing the influence of mining fissure on rock mass integrity and seepage. The evaluation results show that the maximum leakage caused by goaf is 1004.41m³/d, which accounts for 0.87% of the designed annual runoff. As time goes on, the goaf will gradually become stable, and the leakage will decrease little by little over time. In view of the impact on coal mine production safety, it is suggested to strengthen monitoring and early warning.

1. Introduction
Leakage[1-4] is an important issue in the construction of water conservancy projects. At present, the study of reservoir seepage at home and abroad is mainly aimed at the shallow loose stratum of dam foundation or lateral seepage near valley. However, studies of deep stratum of reservoir, especially the stratum with goaf, are rare. Hydraulic engineering construction will break the original balance state of the goaf, so that the surrounding rock mass of the goaf can be reactivated[5-8], which may induce new surface movement deformation, which will bring adverse effects on the stability and leakage of water conservancy facilities. Therefore, it is of great significance to study the influence of mining fissures on reservoir leakage for the construction of water conservancy projects.

2. Project Background
The Hongyan River Reservoir Project in Binzhou City is located on the first tributary of the left bank of Jinghe River in Xianyang City, Shaanxi Province. The project hinge is located at the lower reaches of the main stream of Hongyan River 1 km from the Jinghe Estuary.

The project pivot is composed of dam, flood discharge facility and water conveyance facility. The engineering grade is grade III medium-sized reservoir project. The reservoir dam adopts homogeneous earth dam with the crest elevation of 908.0m, the normal storage water level of 903.0m and the check flood level of 907.6m. The reservoir whose total capacity is 85.15 million cubic metres and the annual water supply is 22.20 million cubic metres plays an important role in solving the problems of low guaranteed water supply rate and insufficient water supply in county towns and local development.

Influenced by coal mining, a large number of cracks appeared on the surface of reservoir area in early 2014. The survey found that the surface cracks were caused by Huoshizui Coal Mine mining 8712 and 8714 working face. In order to reduce the influence of underground mining activities on water conservancy projects, the research work of mining fracture detection and its influence on reservoir leakage was carried out.
Through investigation, the inclination length of 8712 and 8714 working faces in Huoshizui Coal Mine is about 209m, the strike length is about 1980m, the mining direction is pushed from west to east, and the monthly advance speed is 130–240m. Huoshizui Coal Mine adopt fully mechanized top coal caving mining technology at full height, all collapse roof management method. Exploiting No. 4 coal seam, the thickness of coal seam is 7.1m, the height of coal seam floor is 455–465m, and the burial depth is 400–450m. The relative position relationship between the reservoir and the goaf is shown in Figure 1.

The strata in this area are mainly composed of Hujiacun Formation of Upper Triassic, Fuxian Formation of Lower Jurassic, Middle Jurassic (Yan'an Formation, Zhiluo Formation and Anding Formation), Lower Cretaceous (Yijun Formation, Luohe Formation and Huachi Formation), Neogene and Quaternary. The Yan'an Formation of Jurassic is the coal-bearing strata in this area shown in Table 1 for details.

### Table 1. Comprehensive information table for stratigraphy

| Period   | Epoch  | Formation code | Thickness (m) | Lithology description                                                                 |
|----------|--------|----------------|---------------|---------------------------------------------------------------------------------------|
| Quaternary | Holocene | Q4             | 0–20          | Gravel, sand and alluvium.                                                            |
|          | Upper Pleistocene | Q3             | 8–15          | Pale yellow silty sandy loess, loose, homogeneous and large porosity.                   |
|          | Middle Pleistocene | Q2             | 60–130        | Yellowish brown subclay, hard and dense, contains small fossils and 15–18 layers of palaeosol. |
| Neogene  | Pliocene | N              | 40–80         | Brown red clay is rich in cavernous calcium nuclei.                                    |
| Cretaceous | Early | K1h            | 0–120         | The purple mudstone contains the same colored fine sandstone, and there are outcrops at the East and West ends of the mine. |
|          | Luohe | K1l            | 75–358        | The middle and fine grained sandstone of purple red is mudstone and glutenite, thick layered, with large oblique bedding and interlaced bedding. |
|          | Yijun | K1y            | 28–76         | The brown red massive conglomerate consists mainly of quartizite, granite and a small amount of metamorphic rock blocks. |
|          | Anding | J1x            | 10–103        | Purplish red and grayish green sandstones mixed with sand and mudstone and marl lens. |
| Jurassic  | Middle | J2x            | 10–67         | Blue-grey and grey-green coarse sandstone with dark purple mudstone at the top and a layer of grey-white medium and coarse-grained feldspar sandstone at the bottom. |
|          | Zhiluo | J1z            | 10–139        | This layer is rich in plant fossils, gray mudstone at the lower part and thick coal seam, and unstable thick sandstone at the bottom. The middle strata are middle fine sandstone, mudstone and thin coal, and the upper sand mudstone interbeds. |
|          | Early | J1f             | 0–82          | The lower part is medium coarse sandstone breccia and the upper purple red aluminum mudstone. |
Grayish green middle fine sandstone contains mudstone containing gray matter nodules. The mudstone is black and black gray. The structure is dense and the horizontal bedding is extremely developed. After weathering, it becomes a “lens”.

3. Exploration of fractured zone of overlying strata in Goaf

The rock mass around the goaf undergoes more complicated movement and deformation after the coal seam mined out. Qian Minggao[9] thinks that under the condition of full mining, the movement, deformation and failure of the overburden rock appear obvious zoning with showing the characteristics of caving, fracture, separation, movement and deformation, forming “horizontal three zones” and “vertical three zones”.

Through borehole wave velocity and water pressure test, the distribution of overlying rock fracture zone in goaf was detected, and the influence of coal mining on overlying rock structure and permeability characteristics was studied.

Four boreholes were arranged in the test, one of which ZK1 borehole was located outside the influence area of the goaf, and the other three boreholes were located within the influence area of the goaf shown in Figure 1.

3.1. Influence of mining on the integrity of rock mass

Through the wave velocity test, the rock mass integrity ratio of each borehole is shown in Table 2. As the distance from the goaf decreases from 227 m to 34 m, the proportion of broken and fragmented rock mass within 90 m depth increases from 32.1% to 76.5% shown in Figure 2. The proportion of broken and fragmented rock mass within 170 m depth increases from 43.6% to 49.1% shown in Figure 3. With the decrease of the distance from the goaf, the fragmentation degree of rock mass is greatly improved, and the integrity is greatly reduced. The wave velocity of rock mass affected by mining most reduced by 52.7% and 17.16% on average.

| Drill hole | Distance from goaf (m) | Ratio of rock mass integrity within 90m depth (%) | Ratio of rock mass integrity within 170m depth (%) |
|------------|-----------------------|-----------------------------------------------|-----------------------------------------------|
|            | Broken rock mass      | Fractured rock mass                           | Poor integrity rock mass                       | Relatively complete rock mass                  | Broken rock mass | Fractured rock mass | Poor integrity rock mass | Relatively complete rock mass |
| ZK1        | 227                   | 8.6                                           | 23.5                                          | 38.3                                          | 29.6                                           |
| ZK2        | 135                   | 11.4                                          | 35.5                                          | 39.2                                          | 13.9                                           |
| ZK3        | 52.5                  | 18.8                                          | 54.1                                          | 20                                            | 7.1                                            | 9.7                                            | 33.9                                          | 24.9                                          | 31.5                                          |
| ZK4        | 34                    | 4.7                                           | 71.8                                          | 23.5                                          | 0                                              | 2.4                                            | 46.7                                          | 40.6                                          | 10.3                                          |

Figure 2. 90m depth rock mass integrity ratio  
Figure 3. 170m depth rock mass integrity ratio
3.2. Influence of mining on water permeability of rock mass
The results of the water pressure test is shown in Table 3. The analysis shows that as the distance from goaf reduced from 227m to 34m, the ratio of formation thickness with permeability greater than 30Lu within 90m depth is increased from 0% to 81.1% shown in Figure 4, and the ratio of formation thickness with permeability greater than 30Lu within 170m depth is increased from 32.4% to 56.6% shown in Figure 5. The permeability of rock mass increases greatly with the decrease of distance from the goaf. In the same stratum, the permeability of ZK2 borehole is 5.04 times higher than that of ZK1 borehole, the permeability of ZK3 borehole is 5.20 times higher than that of ZK1 borehole, and the permeability of ZK4 borehole is 7.2 times higher than that of ZK1 borehole. According to the test results, the permeability of mining rock mass increased by 5.82 times on average, and mining has a great influence on the permeability of rock mass.

| Drill hole | Distance from goaf (m) | Percentage of permeability distribution of rock mass within 90m depth (%) | Percentage of permeability distribution of rock mass within 170m depth (%) |
|------------|------------------------|-------------------------------------------------|-------------------------------------------------|
|            | q≤10Lu | 10 Lu<q≤20 Lu | 20 Lu<q≤30 Lu | 30 Lu<q | q≤10Lu | 10 Lu<q≤20 Lu | 20 Lu<q≤30 Lu | 30 Lu<q |
| ZK1        | 227    | 44.8         | 47.4          |        |        |        |        |        |
| ZK2        | 135    | 6            | 6             | 32.9   | 47.4   |        |        |        |
| ZK3        | 52.5   | 15.7         | 12.5          | 6      | 59.2   | 45     | 12.8   | 5.9    |
| ZK4        | 34     | 0            | 0             | 11.2   | 81.1   | 22.1   | 3      | 14.3   | 56.6   |

Figure 4. Percentage of permeability distribution of rock mass within 90m depth
Figure 5. Percentage of permeability distribution of rock mass within 90m depth

3.3. The distribution and characteristics of tensile fracture zone at the edge of goaf
The relationship between rock mass integrity index, rock permeability and depth is plotted in Figure 6. According to the graph, there is a good correspondence between the integrity index of rock mass and the permeability of rock mass, and the data are well checked each other.

The analysis shows that the tension fracture zone at the edge of the goaf of 8712 and 8714 working faces in Huoshizui Coal Mine has formed a tension fracture zone with a horizontal width of about 60m shown in Figure 7. The edge of the tension fracture zone is the line formed by the ZK-2 (52.4~69.8m) and ZK-3 (200~223.6m) bands of boreholes, and the whole tension fracture zone is zonal distribution.
3.4. Development height of fractured rock mass

According to the experience of local coal mine, the height of water-conducting fracture zone is about 9~15 times of mining thickness under the condition of 6.9~9.0 m thickness of fully mechanized top coal caving, and its multiple increases when mining thickness exceeds 9m. Preliminary analysis shows that the height of caving zone in the goaf of 8712 and 8714 working faces in Huoshizui Coal Mine is 28.4m and the height of water conduction fracture zone is 106.5 m.

4. Evaluation of leakage in reservoir area by goaf

4.1. Analysis of hydraulic connection between goaf and aquifer and reservoir

According to the analysis of stratum distribution and groundwater occurrence conditions, the direct recharge relationship exists between Hongyanhe reservoir water and Quaternary pore phreatic aquifer, Lower Cretaceous Luohe Formation sandstone fissure water and Yijun Formation glutenite water. The Middle Jurassic Anding Formation is 41.60–104.27 m thick, averaging 78.29 m. It is an important water-proof layer with a wide distribution. According to the geological data, the Jurassic Anding Formation is 102.79m away from the roof plate of coal seam 4-2, and the biggest water conduction fracture in the goaf of 8712 and 8714 working faces of Huoshizui Coal Mine enters the bottom of the Jurassic Anding Formation 3.71m. The cracks in the basin didn’t penetrate the aquifer and have little influence on the seepage. The through-tension fracture zone exists at the edge of the goaf which makes the Luohe sandstone aquifer partly connect with the water-conducting fracture zone of the goaf. The permeability of the stratum is about 5.82 times higher than that of the original stratum.

4.2. Leakage passage

According to the field investigation, the shaft head elevation of Huoshizui Coal Mine is 838.70m, which is 68.9m different from the flood level. The maximum water inflow of the mine is about 735m³/h. It can be concluded that the goaf of Hongyanhe Reservoir is a relative open system, and the water of the reservoir can flow into the goaf from the tension fracture zone and be discharged from the ground through the drainage system of the mine, thus having a leakage channel.
4.3. Calculation method of seepage in goaf and infiltration parameters of rock mass

At present, there is no standard formula for leakage in goaf. Based on Darcy's law and the thought of reservoir seepage calculation theory in "Specification for Hydrogeological Exploration of Water Resources and Hydropower Engineering" (SL373-2007) [10], the formula of goaf seepage calculation is determined as follows: \( Q = k i \omega \).

\( Q \) - Leakage, m/d; \( k \) - Permeability coefficient of rock (soil), m/d; \( i \) - Hydraulic gradient; \( \omega \) - Cross section of water, m².

According to the results of water pressure test, combined with the "Hydrogeology Manual" and considering the disturbance effect of mining on the original stratum, because the fractures are completely communicated, it can be considered that the caving zone is directly connected with the goaf, and the permeability coefficient of the mining rock mass is shown in Table 4.

Table 4. Permeability coefficient of mining rock mass

| Formation code | depth of stratum (m) | Permeability coefficient of original rock mass (m/d) | Permeability coefficient of mining fractured rock mass (m/d) | Remarks |
|----------------|----------------------|------------------------------------------------------|----------------------------------------------------------|---------|
| Q              | 26.5                 | 0.8096                                               | 1.5293                                                   |         |
| K1L            | 42.3                 | 0.8096                                               | 1.3306                                                   |         |
| K1L            | 22.6                 | 0.8096                                               | 1.2096                                                   |         |
| K1L            | 28.3                 | 0.8096                                               | 0.8899                                                   |         |
| K1L            | 13.7                 | 0.8096                                               | 1.3997                                                   |         |
| K1L            | 24.2                 | 0.8096                                               | 0.0449                                                   |         |
| K1L            | 13.2                 | 0.8096                                               | 0.2523                                                   |         |
| K1L            | 30.0                 | 0.8096                                               | 0.0285                                                   |         |
| K1y            | 22.8                 | 0.8610                                               | 0.4026                                                   |         |
| K1y            | 39.8                 | 0.8610                                               | 5.0110                                                   |         |
| J2a            | 32.9                 | 0.0007                                               | 0.0039                                                   |         |
| J2a            | 29.8                 | 0.0164                                               | 0.0955                                                   |         |
| J2y            | 51.4                 | 0.0017                                               | 0.0101                                                   |         |
| J2y            | 21.3                 | 0.0017                                               |                                                          | Caving zone |
| No. 4-2 coal   | 7.1                  | 0.0017                                               |                                                          | Caving zone |

According to the orthogonal seepage formula between groundwater flow direction and layered rock (soil) layer in "Specification for Hydrogeological Exploration of Water Resources and Hydropower Engineering" (SL373-2007), the equivalent permeability coefficient of the whole stratum is 0.0049m/d before mining and 0.0240m/d after mining.

4.4. Evaluation of influence of goaf on reservoir seepage

(1) Maximum leakage under the most unfavorable conditions

The most disadvantageous condition is that the proposed reservoir is located at the maximum flood level, and the leakage is the largest when the water in the reservoir area affected by the goaf enters the goaf for the first time from the tensile fracture zone.

According to the movement angle of the goaf 71 degrees and the horizontal width of the tension fracture zone 60m, the seepage section of 8712 and 8714 working faces in Huoshizui Coal Mine is 46968m² within the checking line of 907.6 flood level shown in Figure 8.
According to the relative relationship between reservoir water level and goaf, the slope of water conservancy is 1.121. According to the calculation, the leakage increased by the influence of goaf is 1004.41m³/d, which accounts for 0.87% of the designed annual runoff of the reservoir.

(2) Long term leakage in reservoir area caused by goaf

With the passage of time, the goaf will gradually become stable and the mining strata will gradually become dense. With the sedimentation of sediment in the reservoir area, some cracks will be filled, and the leakage caused by the goaf will gradually decrease with time.

5. Conclusion

On the basis of wave velocity test and water pressure test, this paper finds out the distribution of overlying rock fracture zone on the edge of goaf, analyzes and evaluates the stability of goaf in reservoir area and its seepage property to reservoir by using seepage theory, and draws the following conclusions:

(1) Through exploration, it is found that there is a tension fracture zone with a horizontal width of about 60m outside of the goaf edge. The permeability of the tension fracture zone is about 5.82 times higher than that of the original stratum, and the water-proof effect of the water-proof layer is lower than that of the original state. Because of the role of the water-proof layer, the goaf will not affect the reservoir leakage in subsidence basin.

(2) The goaf has little influence on the leakage of the proposed reservoir. At the present stage, the maximum leakage caused by the goaf is 1004.41m³/d, which accounts for 0.87% of the designed annual runoff. As time goes on, the leakage of the reservoir area caused by the goaf will gradually decrease.

(3) Reservoir leakage will cause certain safety hazards to coal mine production. Monitoring and early warning should be strengthened to do a good job of surface deformation and mine hydrological observation.

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