Research on Goaf Water Features and Disaster Formation Mechanism in China Coalmines

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Abstract. Goaf water is one of the major water hazards in China coalmines. In statistics, over 80 % of the accidents recorded in the recent years were caused by goaf water burst. This article classifies goaf water into 11 types. It analyses the features of goaf water and studies the mechanisms inducing goaf water disasters, including goaf water exposed by tunnel excavation, channelled by water-conductive faults and post-mining caving fissures in overlying strata, and bursting through damaged water-resistant coal pillar. All achievements can be of reference to other coal-producing countries confronted with karst water hazards.

1. Introduction
Modern coal mining in China started in the early 20th century. With a large number of small coal mines and shallow open mines being shut down, the water accumulated in the goafs and tunnels in the abandoned mines posed great threats to subsequent mining activities. Therefore, goaf water control and treatment was high on the agenda for mining enterprises and scholars. Wu Fahong [1] conducted researches into the goaf water distribution and features in the Linhuan coalmine of Huaibei mining district, Anhui, and proposed technologies to predict and control goaf water. Zhang Jungong [2] worked out the dynamic development pattern and early burst signs of goaf water based on analysis in the No. 2 coalmine of Jining mining district, Shandong, laying the foundation for goaf water control. Luo Liping [3] studied on goaf water in some coalmines of Huainan mining district, Anhui, and explored the features and formation mechanism of goaf water.

The large quantities of water in abandoned mines and goaf space is not only the potential source of water burst, but also alters regional hydrogeological conditions and threatens coalmine safety by raising water level in certain aquifers [4 - 6]. The major and massive water disasters in recent years were mostly attributed to goaf water. Researches into goaf water features and the mechanism inducing goaf water burst are of great significance to effectively manage goaf water and prevent the occurrence of major water disasters [7].

2. Types and features of goaf water hazards
2.1 Types of goaf water
The many types of goaf water in China coal mines can be classified into 11 types based on different principles, including ancient goaf water, modern goaf water, etc., as in Table 1.
Table 1. Classification of goaf water in China coal mines

| Principles          | Type                  | Remarks                                                                 |
|---------------------|-----------------------|-------------------------------------------------------------------------|
| Coalmine shut-down  | Ancient goaf water    | Water in ancient shut-down coalmines (generally refer to before 1960s)   |
| time                | Modern goaf water     | Water in modern shut-down coalmines (generally refer to after 1960s)     |
| Space for water     | Goaf water            | Water in goaf space in shut-down coalmines                              |
| storage             | Tunnel water          | Water in tunnels in shut-down coalmines                                 |
|                     | Shaft (vertical) water| Water in shut-down coalmines excavated by vertical shaft                |
|                     | Footrill water        | Water in shut-down coalmines excavated by footrill                      |
| Mining methods      | Inclined shaft water  | Water in shut-down coalmines excavated by inclined shaft                |
|                     | Dual-shaft water      | Water in shut-down coalmines excavated by vertical-inclined shaft, inclined shaft-footrill, or vertical shaft-footrill |
| Water pH            | Highly acid goaf water| pH<5                                                                     |
|                     | Mild acid goaf water  | pH=5~7                                                                   |
|                     | Neutral water         | pH=7                                                                     |

2.2 Features of goaf water hazards

In the over 500,000 km² coal-bearing region in China, goaf water is the most detrimental [8, 9]. During 2008-2012, among the 99 water-incurred coalmine disasters in record, goaf water was the culprit for 87 or 87.88 % of the total. Summarizing from the past goaf-water-induced coal mine disasters in China, its features include:

1. The extent of damage by ancient and modern goaf water is differentiated
   - In coalmines shut down before the 1960s were mostly small and excavated in shallow depths, leaving narrower goaf or tunnel space. After pressing over a long period of time, water accumulation is limited, causing mine flooding only once in a while but more often production halt or human casualties.
   - In coalmines shut down after the 1960s were mostly large or super large mines. Excavation was much deeper and wider for massive water accumulation, which will cause fatal water burst disasters and heavy human casualties.

2. Goaf water burst is more violent and destructive
   - Goaf water is mostly in static reservation like an underground reservoir. Particularly, modern goaf water, once burst happens, generates enormous amount of water instantly in high pressure and high impact, destroying underground facility and structure in a fleet [10]. On April 19, 2015, in the goaf water burst disaster at the Jiangjiawan coal mine of Shanxi (or known as the 4/19 disaster), instant water burst maximized at 56,956 m³/h, and 21 people were killed.

3. Indicators for imminent goaf water disaster
   - There are signs indicating imminent goaf water burst, for example:
     i. On the working panel, small stream of water first appears and then gradually aggregates to several tens of m³ per hour until abruptly surges to cause burst;
     ii. The small stream is dark in colour with foul smell. The water washes out coal dust, wood shavings, and shreds of canvas air duct (in the small mines before 1980s, canvas air duct was widely used for ventilation in underground mining);
     iii. Pressure on scaffold increases. Crumbs fall from tunnels. Cracks in tunnels, etc.
iv. When drilling exploration holes, hits resistance and coal water burst;
v. Unexpected increase in gas concentration in the airflow around the working panel.

4. Goaf water subsides quickly
   - It takes very short time span from the beginning of goaf water burst to its maximum flow. In minutes, water burst reaches the highest and then quickly subsides to stable and normal water flow in the sandstone fissure aquifer for quite a long time [11, 12]. On Sep. 11, 2003, in the Sangshuping coal mine of Shaanxi, goaf water burst reached its maximum 84,425 m³/h in several minutes and rapidly receded to 40 m³/h. That accident killed 15 people and flooded 404m tunnel.

5. Complex water supply to goaf space
   - In the abandoned mines (before 1960s) which excavated shallow coal seam, water supply to goaf space was primarily atmospheric precipitation and ground water. The water in the subsidence pool fed into the abandoned shallow mines through mining fissures and became goaf water. Due to its close link with ground environment, the water is heavily bicarbonate, neutral or weakly alkaline. In coalmines shut down between 1960s to 1980s, where excavation was deep, water supply to goaf is primarily underground water (such as Cenozoic loose strata water, coal seam sandstone fissure water, etc.), where water environment is rather closed [13, 14].

6. Goaf water is mostly acidic
   - The deep goaf water, being in a closed and reductive environment with low oxygen and high H₂S and CH₄ levels in the air, contains high concentration of SO₄²⁻. The water is low in pH, dominantly acidic, and erosive.

3. Mechanisms inducing goaf water disasters
   By analysing recorded goaf water disasters in China coal mines, the main causals include tunnel excavation exposing goaf water, water-conductive faults channelling goaf water, caving zone or water-conductive fissures in overlying strata channelling goaf water, or goaf water burst through damaged water-resistant coal pillar, etc.

3.1 Goaf water exposed in tunnel excavation
   In China coal mines, when tunnel excavation hits goaf zone, water burst disasters tend to happen more often. This is mainly due to the insufficient knowledge of goaf water distribution. In some cases, when known existence of goaf space is not supported by thorough prospecting or not taken seriously, whereas water volume and criticality are not gauged realistically, blind excavation will breed disaster. On September 18, 1982, during construction of 2135 ventilation uphill tunnel in the Hongqi coal mine of Shuicheng mining district, Guizhou, it hit small faults with a throw of 1.5 m and 0.6 m (Figure 1) and small stream of water burst out. However, it was wrongly judged as water from broken faults and hints of goaf water were missed. With operation proceeding, strong water burst hit after 40 minutes and maximum water volume was 30,000 m³/h, killing 4 people. Post investigation pointed at goaf water as the source of water burst.

3.2 Goaf water channelled by water-conductive faults
   When mining crosses with water-conductive faults which have hydraulic links with goaf water, the latter will gush into the working panel through faults and halt excavation. The situation deteriorates and disaster is due to happen specially if the goaf water is massive in quantity with a water head pressure exceeding the tensile strength of the faults [15, 16]. On July 23, 1985, in the Zaozhuang coal mine of Zaozhuang mining district, Shandong, a goaf water disaster was caused by high-pressured goaf water breaking through broken faults (Figure 2). Water burst was at 3,240~4,680 m³/h (total 25,000 m³), flooding the pump room which was at -300 m.
Figure 1. Scheme of water burst accident at 2135 ventilation uphill tunnel, Hongqi coalmine in Guizhou

3.3 Goaf water channelled by caving fissures in overlying strata
Mining activity will cause caving and fissures in overlying strata. Once the caving zone or water-conductive fissures channel the overhead goaf water, goaf water will be induced to burst and cause water disasters. In Figure 3a, if the water-conductive fissures cracked by mining in 4# coal seam channels goaf water in 3# coal seam, where water volume increases gradually and reaches maximum burst flow over a long period of time, only limited destruction will be caused. In contrast, if the caving zone channels goaf water in 3# coal seam (Figure 3b), water burst will reach its maximum momentarily, the highly pressured and strong currents will cause massive damages.

Figure 2. Faults channelling goaf water in Zaozhuang coal mine in Shandong

Figure 3. Water-flowing through fractured zone channelling goaf water (a) and caving zone channelling goaf water (b)
3.4 Damaged water-resistant coal pillar inducing goaf water burst

It’s been stipulated in the “Regulations on Coalmine Water Control” that water-resistant coal pillars must be retained between mining facility and goaf water to prevent water burst [17]. However, if the water-resistant coal pillars were damaged by human, the tensile strength would be compromised, leaving behind hidden dangers of goaf water burst [18,19]. On December 14, 1982, in the Yangtai coal mine of Xuzhou mining district, Jiangsu, violated the protocol and arbitrarily mined the water-resistant coal pillar segregating Tongtai goaf mine. When excavation reached water prospecting tunnel at -108,32 m (Figure 4), goaf water gushed out and caused maximum burst at 4,698 m³/h and a total of 41,040 m³ water. The accident not only destroyed its own 300 m water prospecting tunnel and water gate wall (capability of 1.5 Mpa), but also shattered and flooded 20,000 m tunnels in the neighbouring Dahuangshan coal mine, where transportation system was partially paralyzed and equipment severely damaged.

Figure 4. Goaf water burst accident in the Yangtai coal mine of Jiangsu

Figure 5. Section diagram of water burst location in Daxing coal mine of Guangdong

In recent years, man-made damages to water-resistant coal pillars have caused frequent goaf water accidents, causing dreadful human casualties and economic losses. On September 11, 1996, in Liujinbao coal mine, Heshan of Guangxi, the illegal mining of the water-resistant coal pillars segregating goaf water undermined the tensile strengths of the pillars, causing goaf water burst in neighbouring Luoguan and Qinyuke coal mines with a total of 1,000,000 m³.

The accident flooded Liujinbao coal mine and the three neighbour coal mines, Qinyucai, Qinyulin, and Luoshancheng, where 38 people were killed.

3.5 Integrated factors contributing to goaf water burst

Usually, the reasons behind goaf water burst are complicated. The combined action of multiple factors, including water-conductive faults, weak water-resistant coal pillar, and coal seam state, can be the integrated factors inducing goaf water burst [20].

At 13:13 on August 7, 2005, during mining at -290 m cross-hole in Daxing coal mine, Meizhou of Guangdong, due to multiple factors, including caving steep coal seam (average at 75°), water-conductive faults, and soaked and weakened water-resistant coal pillar, the overhead goaf water was induced to burst (Figure 5).

Starting at 13:13, the water burst flooded the coal mine at -281 at 13:30. During the 17 minutes, water volume was as high as 231,000 m³.
4. Conclusions

Following conclusions can be drawn based on the above analysis:

- There are in total 11 types of goaf water, such as ancient goaf water from abandoned coal mines before the 1960s, modern goaf water from abandoned coal mines after the 1960s.
- Goaf water is one of the major water hazards endangering China coal mines, causing frequent mine flooding. Recent years in particular, goaf water struck violently in massive volume and high pressure, causing dreadful human casualties and economic losses.
- The main causals to goaf water burst include tunnel excavation exposing goaf water, water-conductive faults channelling goaf water, caving zone or water-conductive fissures in overlying strata channelling goaf water, or goaf water burst through damaged water-resistant coal pillar, etc.

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